UNIVERSITY OF ALBERTA

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DEPARTMENT OF ELECTRICAL ENGINEERING

The Development of a Drill Hole Volume Computer

by

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ABSTRACT

The completion of an oil well requires that the annular space between the well casing and the walls of the drill hole be filled with cement to a prescribed level. The volume of cement required for this operation is usually determined from experience acquired from cementing other wells.

The development of a device which permits the direct determination of the required volume of cement is described. The device was designed to be used in conjunction with commercially available drill hole radius logging equipment. It accepts a signal from the commercial radius measuring tool and continuously computes the drill hole volume. The computed volume is presented in the form of an electrical signal which may be recorded by the equipment normally used to obtain the radius record.

The computer uses electric analog computing elements to perform the required mathematical operations.

Laboratory tests of the development model of the computer showed it to be accurate to within five percent. A theoretical analysis of the computer design showed that an accuracy of one or two percent could be obtained with no changes in the basic design.

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THE DEVELOPMENT OF A DRILL HOLE VOLUME COMPUTER

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THE DEVELOPMENT OF A DRILL HOLE VOLUME COMPUTER

I. INTRODUCTION

The diameter of an oil well drill hole is usually somewhat larger than the nominal diameter of the rotary drilling bit. This is primarily a result of the eroding action of the circulating drilling fluid upon soft, unconsolidated or semi-consolidated formations.

The completion of an oil well invariably involves the insertion of steel casing into the drill hole followed by the pumping of cement slurry into the annular space between the casing and the walls of the hole. Upon setting, the cement provides a seal between the productive formation and other porous fluid bearing formations, and between these formations and the surface.

Good well completion practice dictates that the level of the set cement shall be at least as high as the shallowest potential producing formation penetrated by the drill hole, and to ensure that safe well completions will be made by all operators, most government conservation agencies have regulations which specify the location of the top of the set cement. To comply with such regulations, it is necessary to determine the volume of cement slurry needed to fill the enlarged annular space to the given level.

A common method of determining the required slurry volume involves the addition of a quantity of slurry in excess of the volume between the casing and a hole of nominal bit diameter. The excess slurry volume is statistically determined so as to imply with a high degree of confidence that the enlarged diameter hole of the worst case which might be met in practice will be adequately filled. Such a

procedure is wasteful of cement since the average hole would require a smaller quantity of excess slurry. Furthermore, it is possible that the slurry volume so obtained would not be adequate for every hole and in these cases expensive remedial measures would be required.

A more precise method of slurry volume determination is based upon use of a curve of drill hole diameter or drill hole area versus depth. Such a curve is referred to as a 'caliper log' and is usually run just prior to running the production casing. By means of graphical integration or with the aid of a planimeter, the average hole diameter or area of the section of interest is obtained, and from this the gross hole volume computed. The necessary volume of cement slurry is simply the gross hole volume minus the exterior volume of the casing, both considered over the length of the section.

In practice, the latter method is little used, since it requires the services of a skilled technician at the well. Furthermore, the integration process is laborious and time consuming and indeed might even delay the running of casing with the result that the cost of lost drilling rig time might partially or completely nullify the saving in cement.

The considerations noted above, indicate the need for a log which provides a curve of drill hole volume versus depth. From such a log the volume of the hole between any two points could be read directly, and upon subtracting the casing volume, the required cement slurry volume would be obtained. Such a procedure could be executed by the supervisor in charge of running the casing. It would be simple and no delay would result from its application.

The need for such a log has been recognized for many years by

those associated with the oil industry and the basic principles of two devices which would provide a cumulative drill hole volume log have been described (1,2).

With the hope that oil well logging service companies would become interested in making a volume log available to their clients, and with the further aim of bringing any interest exhibited closer to realization, the development of a drill hole volume computer was undertaken.

II. MATHEMATICAL STATEMENT OF THE PROBLEM

Consider the cross-section of a drill hole depicted in Figure 1. Assuming a circular drill hole, the volume from x = 0 to x = X is given by:

$$V = \pi \int_0^X r^2 \, dx \qquad \ldots\ldots\ldots(1$$

where r = instantaneous drill hole radius

x = instantaneous distance from the bottom of the drill hole

V = volume of drill hole from x = 0 to x = X.

Computation of the drill hole volume by Equation 1 requires integration with respect to distance.

It is possible to rewrite Equation 1 in a form which permits integration with respect to time.

During logging, the depth at which the logging tool is located is a function of time and thus:

$$x = \phi(t)$$

$$\frac{dx}{dt} = \frac{d\,\phi(t)}{dt} = \phi'(t)$$

(1,2) See Bibliography.

The function $\phi'(t)$ may be interpreted as the instantaneous logging velocity.

Changing the variable x in Equation 1 to t we have:

$$V = \pi \int_0^T r^2 \phi'(t)\, dt \qquad \qquad \ldots\ldots\ldots(2$$

where T = time at which logging tool is at x = X.

Since r is a function of time, from Equation 2 it is seen that the volume of the drill hole logged during a time T can be computed by forming the product $r^2 \frac{dx}{dt}$ and integrating this function with respect to time over the period of time T.

III. PRELIMINARY DESIGN OF THE DRILL HOLE VOLUME COMPUTER

Computation of the volume of the drill hole by means of Equation 1 or 2 might be carried out by either a digital or an analog computer.

For computing applications in which errors greater than 0.1 % can be tolerated, an analog machine is usually cheaper and less complex than a digital machine (3). For the problem at hand, the use of an analog machine is indicated since the accuracy requirements are not particularly strict. Furthermore, the input to the computer will be in the form of a continuously varying quantity which the analog machine will accept without the use of costly analog-to-digital converters. From these considerations it is evident that the required computation can be most easily and cheaply accomplished with an analog machine.

As previous discussed, evaluation of the drill hole volume by

application of Equation 1 requires integration with respect to distance. A drill hole volume computer based upon this principle is described in the disclosure of Nance and Rabe (1). This machine uses a mechanical integrator of the ball and disc type (4), the drill hole volume appearing at the output of the machine in the form of a shaft rotation.

The computer described in Reference 2 applies the concepts used in developing Equation 2 and is the basis for the computer described in this dissertation.

A. FUNCTIONAL DIAGRAM OF THE COMPUTER

A functional diagram of the computer which performs the operations required by Equation 2 is shown in Figure 2.

The drill hole radius r is entered into the squarer 1. The squarer output r^2 enters the multiplier 2. The distance signal x is differentiated by the differentiator 3 and its output $\frac{dx}{dt}$ also enters the multiplier. The multiplier forms the product $r^2 \frac{dx}{dt}$ which enters the integrator 4. Integration is carried out with respect to time and thus the integrator output is proportional to $r^2 \frac{dx}{dt}$ which is proportional to the drill hole volume.

B. SPECIFICATIONS

i. <u>Input and Output Signals</u>

The drill hole volume computer was to be developed so as to be compatible with the logging equipment of the Halliburton Oil Well Cementing Company in order that the problems associated with obtaining compatibility with specific logging equipment might be fully appreciated. Thus the computer must accept the electrical radius signal from the Halliburton caliper logging tool and provide an output signal which can be accepted by the

Halliburton recording equipment.

Details of the nature of the caliper tool signal are contained in Appendix A while the output signal requirements are discussed in Appendix B.

ii. Accuracy

A firm specification of the accuracy of the computer was not made at the outset, however it was felt that if the computer was to be of practical value the error in its output and in reading the log should not be greater than 5% of the correct hole volume.

C. SELECTION OF COMPUTING ELEMENTS

i. The Differentiator

Computation of the drill hole volume by the method of Equation 2 requires the derivative of the position of the logging tool with respect to time. Since the caliper tool is pulled up the drill hole by means of a cable, the required derivative will be proportional to the logging cable velocity. All caliper logging systems feed the logging cable over a measuring sheave or drum and therefore the angular velocity of this drum will be proportional to the velocity of the cable. Since the output voltage of a d.c. tachometer is proportional to the angular velocity of its shaft, the output voltage of a tachometer coupled to the measuring sheave will be proportional to the required time derivative.

ii. Squarer and Multiplier

The operation of squaring is essentially that of multiplication. Numerous methods of analog multiplication are discussed in Korn & Korn (5) and Greenwood et al (6) while some direct methods of

squaring are also discussed in Greenwood et al (7).

The computing element used in the drill hole volume computer combines the operations of squaring and multiplication and is based upon the employment of servo positioned potentiometers (8). Figure 3 shows the circuit of the squarer-multiplier.

The differential amplifier drives a servo motor which is coupled to two ganged potentiometers. Potentiometer P_1 is a linear potentiometer whose resistance between the slider and the grounded end is proportional to the shaft rotation θ. Potentiometer P_2 is a square law potentiometer whose resistance between the slider and the grounded end is proportional to the square of the shaft rotation θ. The differential amplifier reacts to the input signals so as to drive the motor in one direction if the algebraic difference between the signals is positive and in the reverse direction if the difference is negative. If the net input signal is zero, the motor does not turn. One input to the amplifier is the voltage E_1 while the other is the fraction of the voltage Y which appears between the slider of P_1 and ground. Thus, the action of the servo motor tends to move the slider of P_1 until:

$$E_1 = \frac{Y}{R_1} \cdot \frac{\theta R_1}{\theta_{max}}$$

where: Y is the voltage applied across P_1

R_1 is the total resistance of P_1

θ is the angle from electrical zero through which the shafts of P_1 and P_2 have turned

θ_{max} is the maximum shaft rotation angle of P_1 and P_2

Therefore:

$$\theta = \frac{E_1 \theta_{max}}{Y} \qquad \text{........(3}$$

Since potentiometers P_1 and P_2 are driven by the same shaft, the slider of P_2 follows the slider of P_1. The output voltage of potentiometer P_2 is the fraction of the voltage E_T applied to P_2 which appears between the slider of P_2 and ground. Thus:

$$E_{slp} = E_T \frac{\theta^2}{\theta^2_{max}} \qquad \text{.......(4}$$

Where: E_{slp} = output voltage of the square law potentiometer

E_T = voltage applied across P_2

Since θ is related to E_1 by Equation 3, substitution for θ in Equation 4 gives:

$$E_{slp} = \frac{E_1^2 \; E_T}{Y^2} \qquad \text{.......(5}$$

In applying the circuit of Figure 3 to the computation of drill hole volume, if E_1 is proportional to the drill hole radius r and if E_T is proportional to the rate of logging $\frac{dx}{dt}$, the output from the squarer-multiplier will be proportional to the product $r^2 \frac{dx}{dt}$. Reference to Figure 2 shows that this is the function which is required at the input to the integrator.

iii. <u>The Integrator</u>

There are numerous methods available for obtaining the time integral of a voltage or current (9). Of those which operate upon a voltage input, the most common is the parallel feedback integrator (10) which utilizes a capacitor in conjunction with a high gain direct coupled amplifier. For integration which must proceed over a long period of time, such integrators suffer from the effects of finite amplifier gain and capacitor leakage in addition to the effect of amplifier drift. Since a caliper log may take as long as two hours to run, the feedback integrator

was not considered practical for use in the computer.

A current integrator of the type described by Watt (11) was chosen for use in the computer. The basic principles of its operation are as follows:

The relationship between the voltage on a capacitor, its capacitance and its charge is given by: $e = \frac{q}{C}$. Differentiating with respect to time,

$$\frac{de}{dt} = \frac{1}{C}\frac{dq}{dt} = \frac{1}{C}\, i \qquad \ldots\ldots\ldots(6$$

where i = current entering the capacitor.

Cross-multiplying Equation 6 by dt and integrating:

$$e_2 - e_1 = \frac{1}{C}\int_{t_1}^{t_2} i\, dt$$

where e_2 and e_1 = voltage on the capacitor at times t_2 and t_1 respectively.

If $e_1 = 0$ when $t_1 = 0$,

$$E_C = \frac{1}{C}\int_{o}^{t} i\, dt \qquad \ldots\ldots\ldots(7$$

where E_C = voltage on capacitor due to current i flowing into initially uncharged capacitor for a time t.

Thus the voltage rise on the capacitor is proportional to the time integral of the current entering the capacitor.

It will be recalled from Figure 2 that the time integral of

the quantity $r^2 \frac{dx}{dt}$ is required. The squarer-multiplier produces a voltage proportional to this quantity and in order to use the capacitor integrator it is necessary to obtain a current which is proportional to $r^2 \frac{dx}{dt}$. The means by which this is accomplished and the circuit of the integrator is shown in Figure 4.

The differential amplifier drives a servo motor which is coupled to the shaft of potentiometer P_4, across which is connected a voltage source E_B. The slider of the potentiometer is connected to the control grid of the pentode current controller tube, while a tap on the potentiometer is connected to the lower end of the cathode resister R_k. The tube obtains its plate voltage from the voltage source E_p and the circuit from the pentode cathode is returned to E_p through R_k, the integrating capacitor C and a resistor R_3.

The magnitude of the current i flowing in the plate and cathode circuits of the pentode is controlled by the position of the slider of potentiometer P_4. As the slider moves toward the positive end of P_4 the current i will increase, while if the slider moves in the opposite direction current will decrease, finally approximating zero.

The differential amplifier reacts to its input signals so as to drive the motor-potentiometer combination in such a fashion as to make the input to the amplifier zero. Since one input is the voltage E_{slp} and the other is the voltage drop across R_3, the current i is controlled so that:

$$E_{slp} = i R_3 \qquad \text{........(8}$$

Since i enters the capacitor C, the voltage rise on the capacitor is given by:

$$E_C = \frac{1}{C} \int i \, dt = \frac{1}{C R_3} \int E_{slp} \, dt$$

Since E_{slp} is proportional to $r^2 \frac{dx}{dt}$, the voltage across the capacitor will be proportional to the drill hole volume.

iv. The Basic Circuit of the Drill Hole Volume Computer

The computing elements described above may be combined to form the basic circuit of the computer as shown in Figure 5.

The caliper logging tool is pulled up the drill hole by means of the logging cable which travels over a measuring sheave. The tachometer is connected to the measuring sheave and thus the shaft rotation of the tachometer is proportional to the rotation of the measuring sheave. The logging tool produces a voltage E_r which is proportional to the drill hole radius r. The voltage E_r is balanced against a voltage obtained from the linear potentiometer by servo amplifier 1 and thus a shaft rotation θ proportional to r is obtained. Connected to the shaft of the linear potentiometer is the square law potentiometer which is fed the voltage E_T produced by the tachometer. The voltage E_T is proportional to the logging velocity dx/dt. The output voltage of the square law potentiometer E_{slp} is proportional to the product of θ^2 and E_T. Since θ is proportional to r, E_{slp} is proportional to $r^2 \, dx/dt$. Through the action of servo amplifier 2, a current which is proportional to E_{slp} is produced in the cathode circuit of the current controller tube. This current enters the integrating capacitor and thus the capacitor voltage rise will be proportional to the time integral of the current. There-

fore E_C will be proportional to $\int r^2 \frac{dx}{dt}\, dt = \int r^2\, dx$ which is in turn proportional to the volume of the drill hole.

D. CALIBRATION OF THE COMPUTER

In the preceding section, it was shown that the voltage across the integrating capacitor will be proportional to the drill hole volume. In order to make the computer of practical value, it is necessary to establish the constant of proportionality between the computer output voltage and the drill hole volume. This may be done by considering the 'scale factors' which define the relationship between a given variable of the physical problem to its analogous machine variable, and finding the 'transfer functions' which relate the output of the respective computing elements to their respective inputs. From these relationships the transfer function of the computer as a whole can be determined and finally the desired constant of proportionality obtained.

The scale factor α may be defined as (12):

$$\alpha = \frac{\text{Magnitude of quantity representing computer variable}}{\text{Magnitude of corresponding physical variable}}$$

The transfer function β may be defined as (13):

$$\beta = \frac{\text{Computer (element) output}}{\text{Computer (element) input}}$$

The choice of scale factors is usually at the discretion of the computer designer. The scale factor for a given variable should be large in order that errors caused by uncontrollable perturbations of the computer variable will be minimized, however the maximum value of a scale factor is limited by the maximum value which the computer variable may assume. Thus in choosing scale factors, a compromise between these

conflicting considerations must be made.

The transfer function of a given computing element may be fixed by its mechanical or electrical characteristics, or it may be subject to alteration by a suitable choice of its constituent components.

The scale factors to be chosen for the drill hole volume computer are given in Table I, while the transfer functions are defined in Table II.

TABLE I

Physical Variable	Computer Variable	Scale Factor
r Drill hole radius Feet	θ Angular shaft rotation, degrees	$\alpha_1 = \frac{\theta}{r} \frac{\text{degrees}}{\text{foot}}$
$\frac{dx}{dt}$ Rate of logging Feet/second	ω Tachometer shaft angular velocity Degrees/second	$\alpha_2 = \frac{\omega}{\frac{dx}{dt}} \frac{\text{degrees}}{\text{foot}}$
V Drill hole volume Cubic feet	E_c Integrating capacitor voltage Volts	$\alpha_3 = \frac{E_c}{V} \frac{\text{volts}}{\text{ft}^3}$

TABLE II

Computing Element	Computing Element Input	Computing Element Output	Transfer Function
Tachometer	ω deg/sec	E_T volts	$\beta_1 = \frac{E_T}{\omega} \frac{\text{volt sec}}{\text{degree}}$
Square Law Potentiometer	E_T volts	E_{slp} volts	$\beta_2 = \frac{E_{slp}}{E_T} = \frac{\theta^2}{\theta^2_{max}}$
Integrator	i amperes	E_c volts	$\beta_3 = \frac{E_c}{i} = \frac{1}{CP} \frac{\text{volts}}{\text{ampere}}$

Where: θ_{max} is the maximum rotation of linear and square law potentiometer shafts

P is the operator $\frac{d}{dt}$

The transfer function for the complete computer may be derived by starting with the transfer function for the output stage of the computer and substituting for each successive input variable until the input stage of the computer is reached.

Thus from the definition of β_3,

$$E_c = \frac{i}{CP} \qquad \ldots\ldots\ldots(9$$

It will be recalled that Servo-amplifier 2 controls the current i so that Equation 8 is satisfied. Therefore, we have the relation:

$$E_{slp} = i\, R_3 \qquad \ldots\ldots\ldots(8$$

Substituting for i in Equation 9,

$$E_c = \frac{E_{slp}}{R_3 CP} \qquad \ldots\ldots\ldots(10$$

Substituting for E_{slp} from the definition of β_2,

$$E_c = \frac{\theta^2 E_T}{\theta^2_{max} R_3 CP} \qquad \ldots\ldots\ldots(11$$

Substituting for E_T from the definition of β_1,

$$E_c = \frac{\theta^2_{\omega} \beta_1}{\theta^2_{max} R_3 CP} \qquad \ldots\ldots\ldots(12$$

Equation 12 defines the relationship between the output of the computer E_c and its input $\theta^2 \omega$. Thus the computer transfer function is given by,

$$\beta_c = \frac{E_c}{\theta^2 \omega} = \frac{\beta_1}{\theta^2_{max} R_3 CP} \qquad \ldots\ldots\ldots(13$$

If β_c is specified, then the transfer function β_1 and the computer constants θ_{max}, R_3 and C must be selected so as to satisfy Equation 13.

Equation 13 defines the computer transfer function in terms of the machine variables. If the machine variables are written in terms of the corresponding physical problem variables, as defined by the scale factors α_1, α_2 and α_3, we have after substituting and re-arranging terms:

$$PV = \frac{dV}{dt} = \frac{\alpha_1^2 \alpha_2 \beta_1}{\alpha_3 R_3 C \theta^2_{max}} r^2 \frac{dx}{dt} \qquad \ldots\ldots\ldots (14$$

Integrating both sides of Equation 14,

$$\int_0^V dV = V = \frac{\alpha_1^2 \alpha_2 \beta_1}{\alpha_3 R_3 C \theta^2_{max}} \int_0^X r^2 \, dx \qquad \ldots\ldots\ldots (15$$

But from Equation 1,

$$V = \pi \int_0^X r^2 dx \qquad \ldots\ldots\ldots (1$$

Therefore:

$$\frac{\alpha_1^2 \alpha_2 \beta_1}{\alpha_3 R_3 C \theta^2_{max}} = \pi \qquad \ldots\ldots\ldots (16$$

Equation 16 expresses the relationship between the scale factors α_1, α_2 and α_3, the transfer function β_1, and the computer constants R_3, C and θ_{max} which must be satisfied if a given computer calibration is to be obtained. It will be noted that fixing any six of the factors in Equation 16 determines the seventh.

Equation 16 will be applied in the final design of the computer.

In connection with the design of the current controller circuit, it is necessary to determine the current requirements of the integrating circuit. This may be done as follows:

From Equation 8,

$$i = \frac{E_{slp}}{R_3} \qquad \text{........(17}$$

Substituting for E_{slp} from the definitions of $\alpha_1, \alpha_2, \beta_1$ and β_2,

$$i = \frac{\alpha_1 \alpha_2 \beta_1}{\theta^2_{max} R_3} \; r^2 \frac{dx}{dt} \qquad \text{........(18}$$

Since R_3 is defined by Equation 16, upon substitution in Equation 18,

$$i = \pi \alpha_3 \, C \, r^2 \frac{dx}{dt} \qquad \text{........(19}$$

The maximum current will be required when r and dx/dt take their maximum values, therefore:

$$i_{max} = \pi \, \alpha_3 \, C \, r^2_{max} \left(\frac{dx}{dt}\right)_{max} \qquad \text{.......(20}$$

E. THEORETICAL PERFORMANCE ANALYSIS OF THE PRELIMINARY COMPUTER DESIGN

A theoretical analysis of the performance of a computer design will indicate whether or not, in the light of available data, the computer will operate satisfactorily. Such an analysis should account for the errors in the computer solution due to the inaccuracies of the individual computer elements, deviation from ideal performance of any elements and the effects of environment upon the operation of the computer elements.

The most important phase of the performance analysis is the investigation of errors due to the inaccuracies of the individual computing elements, for upon this will depend the ultimate specification of the allowable computing element inaccuracy. Since the cost of a component increases rapidly with reduction in inaccuracy, an economical design will result only when component inaccuracies are no lower than necessary to obtain the re-

quired performance. An error analysis may even show that the required accuracy cannot be obtained with components having the lowest inaccuracy available. In such a case, it would be necessary to relax the accuracy requirements of the computer or alter its design, repeating the performance analysis to ascertain if the new design will meet requirements.

i. Analysis of Computer Error due to Computing Element Inaccuracies

The total computer error caused by the inaccuracies of the individual computing elements may be calculated by two different methods. The first method assumes that the maximum computing element inaccuracies occur simultaneously and affect the computer output in the same direction. An error calculated in this manner may be called the 'computer limiting error.' The second method associates an individual probable error (14) with each element and combines these to obtain the 'computer probable error.' The individual probable errors are usually taken as one-third the peak error or tolerance of the computing element and are combined by squaring and summing the individual probable errors and taking the square root of the resulting total. The latter method is most often used in practice (15) and it has been suggested that the results so obtained may be expected to be correct within a factor of two (16).

a. Output inaccuracy of linear potentiometer:

The linear potentiometer is used to obtain a shaft rotation which is proportional to a voltage which is itself proportional to the drill hole radius.

As discussed in Section III C, Subsection ii, and as shown in Figure 3, the servo-amplifier adjusts the angular position of the linear potentiometer shaft until:

$$E_1 = \frac{R'_1}{R_1} \quad Y \qquad \ldots\ldots\ldots(20$$

where:

R_1 = total resistance of potentiometer P_1

R'_1 = fraction of the total resistance between the slider of P_1 and ground

Y = reference voltage

If the potentiometer is truly linear:

$$_IR'_1 = \frac{\theta}{\theta_{max}} R_1 \qquad \text{........(21}$$

where:

$_IR'_1$ = resistance function of ideal linear potentiometer

θ = angular displacement of the shaft of P_1 referred to $R'_1 = 0$

θ_{max} = maximum angular displacement of shaft of P_1

Due to errors in manufacture or construction, the above equation must be replaced by:

$$R'_1 = \frac{\theta}{\theta_{max}} R_1 + \Delta R_1 \qquad \text{........(22}$$

where ΔR_1 = peak error of potentiometer P_1.

Substituting in Equation 20 for R'_1 as defined by Equation 22:

$$E_1 = \frac{\theta}{\theta_{max}} Y + \frac{\Delta R_1}{R_1} Y$$

Solving for θ:

$$\theta = \frac{E_1}{Y} \theta_{max} \pm \frac{\Delta R_1}{R_1} \theta_{max}$$

or:

$$\theta = \frac{E_1}{Y} \theta_{max} \pm T_1 \theta_{max} \qquad \text{........(23}$$

where: $T_1 = \frac{\Delta R_1}{R_1}$ = fractional tolerance of potentiometer P_1.

b. Output Inaccuracy of Square Law Potentiometer:

The output voltage of the square law potentiometer P_2 is given by:

$$E_{slp} = \frac{R'_2}{R_2} E_T \qquad \text{........(24}$$

where R_2 = total resistance of potentiometer P_2

R'_2 = fraction of total resistance appearing between the slider of P_2 and ground

E_T = voltage from tachometer applied across P_2.

If the potentiometer resistance conforms exactly to the desired square law function,

$$_IR'_2 = \frac{\theta^2}{\theta^2_{max}} R_2$$

Where:

$_IR'_2$ = resistance function of ideal square law potentiometer

Due to errors in manufacture or construction, the actual potentiometer resistance function R'_2 is given by:

$$R'_2 = \frac{\theta^2}{\theta^2_{max}} R_2 \pm \Delta R_2 \qquad \text{........(25}$$

Where:

ΔR_2 = peak error of potentiometer P_2.

Substituting in Equation 24 for R'_2 as defined by Equation 25:

$$E_{slp} = \frac{\theta^2}{\theta^2_{max}} E_T \pm T_2 E_T \qquad \text{........(26}$$

where: $T_2 = \frac{\Delta R_2}{R_2}$ = fractional tolerance of potentiometer P_2.

c. Output inaccuracy of tachometer:

The output voltage of an ideal tachometer is proportional to the angular velocity of its shaft.

Thus:

$${}_I E_T = \beta_1 \omega$$

where:

${}_I E_T$ = voltage output function of ideal tachometer

ω = tachometer shaft angular velocity

β_1 = tachometer transfer function

Due to errors in manufacture or construction, the actual output voltage of the tachometer is given by:

$$E_T = \beta_1 \omega \pm T_T \; E_{Tmax} \qquad \text{.........(27}$$

where $E_{T\,max}$ = full scale output voltage of tachometer

T_T = fractional linearity tolerance of tachometer

d. Output inaccuracy of potentiometer-tachometer combination:

The error in the output of the computer due to the inaccuracies of the linear and square law potentiometers and the tachometer may be found as follows:

The output voltage of the square law potentiometer is given by Equation 26:

$$E_{slp} = \frac{\theta^2}{\theta^2_{max}} E_T \pm T_2 E_T \qquad \text{.........(26}$$

Substituting for θ and E_T as given by Equations 23 and 27, neglecting products and squares of tolerances and writing E_T for ${}_I E_T$,

$$E_{slp} = \frac{E_1{}^2 E_T}{Y} \pm \frac{2E_1 E_T T_1}{Y} \pm E_T T_2 \pm \frac{E_1{}^2}{Y^2} E_{T\,max} \; T_T \qquad \text{....(28}$$

The error in the output of the square law potentiometer is given by the last three terms of Equation 28, or:

$$\Delta E_{slp} = \frac{2E_1 E_T T_1}{Y} \pm E_T T_2 \pm \frac{E_1^2}{Y^2} E_{Tmax} \; T_T \qquad \text{........(29}$$

The fractional error in E_{slp} is given by:

$$(\varepsilon)_{slp} = \frac{\Delta E_{slp}}{E_{slp}} = \frac{\Delta E_{slp}}{\frac{E_1^2 E_T}{Y^2}} = \pm \frac{2YT_1}{E_1} \pm \frac{Y^2 T_2}{E_1^2} \pm \frac{E_{Tmax}}{E_T} T_T \qquad \ldots\ldots\ldots(30$$

From Equations 20 and 21,

$$\frac{Y}{E_1} = \frac{\theta max}{\theta}$$

and upon substituting in Equation 30, the fractional error in the output of the square law potentiometer is given by:

$$(\varepsilon)_{slp} = \pm \frac{2\theta max}{\theta} T_1 \pm \frac{\theta^2 max}{\theta^2} T_2 \pm \frac{E_{Tmax}}{E_T} T_T \qquad \ldots\ldots\ldots(31$$

From the earlier discussion of the combination of individual computing element errors, the limiting error is given by:

$$\text{limiting } (\varepsilon)_{slp} = \frac{2\theta max\ T_1}{\theta} + \frac{\theta^2 max\ T_2}{\theta^2} + \frac{E_{Tmax}\ T_T}{E_T} \qquad \ldots\ldots\ldots(32$$

and the probable error is given by:

$$\text{probable } (\varepsilon)_{slp} = \frac{1}{3}\left(\frac{4\theta^2 max T_1^2}{\theta^2} + \frac{\theta^4 max\ T_2^2}{\theta^4} + \frac{E_{T\ max}^2\ T_T^2}{E_T^2}\right)^{\frac{1}{2}} \qquad \ldots\ldots(33$$

Equations 32 and 33 are plotted on Figure 6 for $T_1=T_2=T_T= 0.5\%$ and on Figure 7 for $T_1=T_2= 0.2\%$ and $T_T = 0.5\%$. For the curves shown on both figures, $E_{T\ max}/E_T = 5.0$. The latter expresses the ratio between the maximum and minimum rate of logging and is the most unfavourable ratio which would obtain in practice. It will be noted that the abscissae of Figures 6 and 7 may be interpreted as either θ_{max}/θ or r_{max}/r, since θ is proportional to r.

If the minimum nominal hole radius which would be logged in practice is taken as 3.75 inches and if r_{max} = 15 inches, then r_{max}/r= 4.0 and from Figure 6, the limiting error would be 14.5 % and the probable

error would be 3.1 %.

From Section II B, Subsection ii, the maximum allowable error of the computer was quoted as 5%. Thus, if one chooses to accept the probable error listed above, potentiometer and tachometer tolerances of 0.5 % may be specified. This specification should be satisfactory since the drill hole radius will be considerably larger than the minimum quoted above and the logging rate will normally approach the maximum permissable velocity over the greater part of the hole. Therefore, the actual error which would be observed in practice should be somewhat lower than the figures quoted above.

If this should not be the case, Figure 7 shows that by decreasing the tolerance of the potentiometers to 0.2%, the limiting and probable errors for $r_{max}/r = 4$ are 7.3% and 1.4% respectively, which should permit an accuracy better than 5% to be obtained.

From the foregoing, it is seen that the preliminary design should be satisfactory from the standpoint of errors introduced by the potentiometers and the tachometer.

ii. Analysis of Capacitor Integrator Errors

The voltage rise on the integrating capacitor is given by:

$$E_c = \frac{1}{C}\int_0^t i\,dt \qquad \text{.........(7}$$

E_c will be proportional to the drill hole volume logged during the time t if i satisfies Equation 19:

$$i = \pi \alpha_3 C r^2 \frac{dx}{dt} \qquad \text{.......(19}$$

If the integrating capacitor has a leakage resistance R_L, a portion of the current given by Equation 19 will not enter the capacitor and thus the voltage E_C will not be a true representation of the drill

hole volume logged.

A second source of error is caused by the nature of the current controller circuit. Equation 19 requires that the current i be zero if dx/dt is zero (i.e. if logging is temporarily stopped during a run). It is not possible for the output of the current controller pentode shown in Figures 4 and 5 to be exactly zero and therefore a small current will enter the integrating capacitor when logging is suspended. The result is an error in the voltage E_C.

It should be noted that the error due to leakage opposes that caused by the residual controller current and thus when logging is halted the two errors tend to compensate.

Limits for the integrating capacitor leakage resistance and the residual controller current can be established such that the errors incurred will be smaller than some specified amount. This can be done as follows.

Referring to Figure 8, consider an ideal capacitor C shunted by a resistor R_L representing the capacitor leakage resistance. The current i of which the time integral is required splits into two components, i_c entering the capacitor and i_r entering the resistor.

The desired integral is represented by:

$$I = \int_0^{t_i} i \, dt$$

where t_i = period of time over which integral is evaluated.

Since $i = i_c + i_r$,

$$I = \int_0^{t_i} i_c \, dt + \int_0^{t_i} i_r \, dt.$$

Let e be defined as:

$$e = \frac{1}{C}\int_0^{t_i} i_c \, dt \qquad \text{.......(34}$$

where e = voltage across the initially uncharged capacitor after t_i

and since $i_r = \frac{e}{R_L}$

$$\frac{I}{C} = e + \frac{1}{CR_L}\int_0^{t_i} e \, dt$$

If one measures the voltage e and takes it as the value of the desired integral at time t_i, the error suffered is equal to:

$$\frac{\Delta I}{C} = \frac{1}{CR_L}\int_0^{t_i} e \, dt ,$$

and the fractional error suffered is given by:

$$\frac{\Delta I}{I} = \frac{\frac{1}{CR_L}\int_0^{t_i} e \, dt}{e} \qquad \text{.......(35}$$

To evaluate the magnitude of the error, it is necessary to know the function e. An approximation to this function can be made by assuming that the current i is constant (which implies a constant drill hole radius).

If we let $i = a$ where a is a constant,

$$i_c = a - i_r.$$

Since i_r is to be made small relative to a, we may say that $i_c = a$.

Substituting for i_c in Equation 34,

$$e = \frac{1}{C}\int_0^{t_i} a \, dt = \frac{at}{C}$$

Substituting for e in Equation 35,

$$\frac{\Delta I}{I} = \frac{t_i}{2\ CR_L}$$

If the fractional error is to be made smaller than some fraction p, then:

$$P > \frac{t_i}{2\ CR_L}$$

and thus

$$R_L > \frac{t_i}{2\ pC} \qquad \ldots\ldots\ldots(36$$

Equation 36 permits a minimum value for R_L to be specified for integration lasting for a period of time t_i with a fractional error less than p.

An expression for the maximum residual controller current may be developed as follows.

The change in the voltage across the integrating capacitor C due to the flow of residual controller current i_{res} into the capacitor is given by:

$$\Delta e = \frac{1}{C} \int_0^{t_s} i_{res}\ dt$$

where t_s = period over which logging has been stopped

Since i_{res} is constant,

$$\Delta e = \frac{i_{res}\ t_s}{C}$$

If Δe is to be made less than some fraction p of the maximum integrating capacitor voltage $E_{C\ max}$,

$$p\ E_{C\ max} > \frac{i_{res}\ t_s}{C}$$

$$\text{or} \qquad i_{res} < \frac{pC\ E_{C\ max}}{t_s} \qquad \ldots\ldots(37$$

Equation 37 permits the maximum value of the residual current-controller current to be specified.

iii. Effect of Environment Upon the Computer Output

a. Temperature:

Changes in temperature may affect the output of the tachometer and also cause a change in value of the resistive and capacitive elements.

A search of the literature and manufacturers' specifications for information regarding the temperature dependent performance of tachometers was not fruitful and in order to evaluate this effect, measurements were made on the tachometer which was to be used in the computer. These measurements indicated a tachometer temperature coefficient of output voltage of less than .01%/°C. Thus, if the tachometer transfer function is determined at a given ambient temperature, variations of $\pm$ 20°C about this ambient will result in an error due to temperature of .2% of full scale voltage. This performance is regarded as satisfactory.

The output of the potentiometers will not be affected by changes in temperature since they are operated as voltage dividers and temperature changes will affect the resistance on each side of the dividing point in the same proportion.

The remaining resistive elements in the computer are the controller tube cathode resistor R_k and the resistor R_3 (See Figure 5).

Changes in R_k which will result in a change of the controller output current will be compensated for automatically by the self-balancing characteristics of the servo-amplifier motor system.

Changes in the value of R_3 must be carefully considered, however, since the controller output current is given by Equation 17 as:

$$i = \frac{E_{slp}}{R_3} \qquad \text{........(17}$$

and therefore i is affected inversely by changes in R_3. Thus, R_3 must have a low temperature coefficient of resistance. If a change in R_3 of 0.2% is to be permitted for an ambient temperature change of 20°C, the maximum temperature coefficient of resistance will be .01%/°C. This can be achieved without difficulty since resistance wire having a temperature coefficient of resistance as low as .002%/°C is available.

High quality plastic film capacitors are little affected by temperature changes. A representative temperature coefficient of capacity is .01%/°C and therefore a change of 20°C would result in a capacitance change of only 0.2%.

b) Humidity:

As discussed previously, the leakage resistance of the integrating capacitor is important to the performance of the computer. The leakage resistance of the capacitor itself can be maintained at a high value by specifying a hermetically sealed unit having glass terminals. Since external connections must be made to the capacitor, care must be used in choosing the insulation between these external connections and ground in order that this insulation will not be adversely affected by high humidity. Satisfactory performance can be effected by using insulating materials such as glazed porcelain, polystyrene, nylon, polyethylene or Teflon.

IV. FINAL COMPUTER DESIGN

The following discussion will be limited to an exposition of the application of the principles discussed in the previous section insofar as they affect and control the specification of the electrical components used in the computer. A complete discussion of the computer design is contained in Appendix B.

A. SERVO AMPLIFIER 1 AND THE LINEAR POTENTIOMETER

As discussed in Section III C, Subsection ii and referring to Figure 5, servo amplifier 1 balances the radius signal E_r against the output of potentiometer P_1 so as to obtain a shaft rotation θ which is proportional to the drill hole radius r. From Appendix A, the magnitude of E_r corresponding to the maximum hole radius will be approximately one volt. This specifies the reference voltage Y shown in Figures 3 and 5. As discussed in Appendix B, a means of adjusting this reference voltage is provided in order that it may be made equal to $E_{r\ max}$.

The servo amplifier must be able to accept a signal of the order of one volt and provide sufficient output to drive the servo motor. For this purpose a standard Minneapolis-Honeywell Brown servo system (17) using a 27 rpm motor directly coupled to the potentiometers was specified. The Brown amplifier is designed to operate from a signal source having a maximum impedance of a few thousand ohms. Since the Halliburton caliper signal source impedance is of the order of 100,000 ohms, an impedance matching preamplifier must be inserted between the caliper tool output and the input to the servo amplifier. The circuit details are contained in Appendix B.

From the results of the theoretical performance analysis, a Technology Instrument Corporation Type RV 1 5/8 linear potentiometer having a linearity tolerance of 0.5% was specified for P_1. This potentiometer has an electrical rotation angle of 350^{o}, which must therefore correspond to the maximum drill hole radius r_{max}. If r_{max} is taken as 15 inches or 1.25 feet, the corresponding scale factor α_1 = 280 degrees/foot.

B. THE TACHOMETER

The tachometer produces an output voltage which is to be proportional to the rate of logging dx/dt. The shaft of the tachometer will be driven by a selsyn motor which is to be excited by the Halliburton master selsyn generator which in turn is coupled to the logging cable measuring sheave. The shaft of the Halliburton selsyn generator turns three revolutions for each foot of cable passing over the measuring sheave and thus the tachometer selsyn and the tachometer itself will follow. The corresponding scale factor will therefore be α_2 = 1080 degrees/foot.

An Instrument Motors Type M-24-012 tachometer was specified for use in the computer. This tachometer has a linearity tolerance of 1% for a speed range up to 5000 rpm. The maximum caliper logging speed is 150 feet/min. and therefore the maximum tachometer speed will be 450 rpm. The linearity of this tachometer in the speed range 0 to 450 rpm was found to be approximately 0.5% which is the same as the linearity requirements suggested by the theoretical performance analysis. The output of the tachometer was found to be 0.9882 volts per 100 rpm and therefore the transfer function of the tachometer is β_1 = 0.1647 x 10^{-2} volt seconds/degree.

C. THE SQUARE LAW POTENTIOMETER

A Technology Instrument Corporation Type RV 1 5/8 - S347 square law potentiometer having a conformity of 0.5% was specified for use in the computer. The unit has an electrical rotation angle of 350° which is the same as that of the linear potentiometer. The linear and square law potentiometers are mounted on the same shaft and their sliders were phased by the manufacturer so that the resistance between the sliders and the resistance function = 0 terminal of each potentiometer was zero when the electrical rotation angle was zero.

The total resistance of the potentiometer as measured by the manufacturer is 9867 ohms.

The maximum electrical angle of rotation of both potentiometers defines θ_{max} and therefore θ_{max} = 350 degrees.

D. THE COMPUTER OUTPUT SCALE FACTOR

Before the values of the components comprising the remaining elements of the computer can be specified, it is necessary to set the computer output scale factor. This scale factor, designated by α_3 relates the integrating capacitor voltage to the volume of drill hole logged. A convenient maximum voltage for the integrating capacitor to attain is 300 volts. The drill hole volume which this voltage is to represent is not so simply chosen.

If the full scale deflection on the drill hole volume record is to represent the total volume of the deepest and largest hole which might be met in practice, it would have to represent a volume of the order of 50,000 ft^3. Since a record a few inches wide may be read to the nearest 0.1%, the corresponding reading accuracy would be 50 ft^3.

Suppose this same instrument is used to log a smaller hole, which for argumentative purposes, let us say has an average radius of four inches. The volume of 500 lineal feet of the hole is 175 ft^3. If this volume were read from a chart having the full scale calibration postulated above, the uncertainty in reading the required volume would be almost 30%.

Although the full scale calibration of the drill hole volume record could be varied so as to be only somewhat larger than the anticipated volume of the specific hole being logged, such a procedure would not be entirely satisfactory.

The following is a description of the method of presenting the drill hole volume information which was finally adopted.

The maximum voltage of the integrating capacitor represents a definite and constant volume. The full scale deflection of the volume chart represents this same volume. When the integrating capacitor charges to its maximum voltage, a trigger circuit operates a relay which discharges the capacitor, after which the relay opens and permits the capacitor to recharge. The volume record reflects the performance of the capacitor, going from the full scale volume deflection to zero volume, then recording the volume of the next increment of hole logged as the capacitor recharges. The type of record which would be thereby obtained is shown in Figure 9. In interpreting the record, the volume between two given depths would be obtained by counting the number of times the full scale increment of hole volume had been reached and adding to this the volume of hole between the depths of interest and the adjacent full scale deflection return lines.

Details of the system whereby the triggering of the capacitor discharge relay is effected are contained in Appendix B.

A convenient full scale volume calibration is 500 ft^3. The reading accuracy such a chart would be 0.5 ft^3 and the uncertainty in reading a volume would be less than 1% for volumes greater than 10 ft^3.

If the maximum integrating capacitor voltage is 300 volts and if this represents 500 ft^3 of hole volume, the scale factor $\alpha_3 = 0.6$ volts ft^3.

E. THE INTEGRATING CAPACITOR

The capacitor used in the integrating circuit must meet certain requirements. It must have a high leakage resistance and must also be stable and have a low temperature coefficient of capacity. Since the capacitor is to be momentarily discharged during a run, it must have a low dielectric absorption. These requirements can be met by the specification of plastic film dielectric capacitors (18).

"Stabelex D" plastic film capacitors manufactured by the Industrial Condenser Corporation were specified for use in the drill hole volume computer. These capacitors have the following characteristics (19):

Leakage resistance-capacity product or self-time constant:

at 15°C	1.5×10^6 seconds
at 30°C	1.0×10^6 seconds
at 45°C	0.5×10^6 seconds

Temperature coefficient of capacity: 0.01%/°C

Dielectric absorption after 10 millisecond discharge through one ohm: less than 0.1% of initial charging voltage

Preliminary calculations suggested that a nominal capacitance of 20 microfarads would be desirable in the integrating circuit. Later development work confirmed this as a satisfactory choice. Measurements

made upon the delivered capacitors (consisting of two units of 10 microfarads each) determined their actual total capacitance as 21.5 ± 0.1 microfarads.

Knowledge of the integrating capacitor capacitance permits specification of its minimum leakage resistance. From Equation 36:

$$R_L > \frac{t_i}{2\ pC} \qquad \text{........(36}$$

The maximum period of time over which current integration will procede is given by:

$$t_i = \frac{V}{\pi r^2_{min} \left(\frac{dx}{dt}\right)_{min}}$$

where: V = drill hole volume represented by fully charged capacitor

r_{min} = minimum drill hole radius

$(dx/dt)_{min}$ = minimum logging velocity

Since V has been chosen as 500 ft^3, r_{min} = 0.3125 ft and $(dx/dt)_{min}$ = 0.5 ft/sec,

t_i = 3260 seconds

If the fractional error p in the integrated current is to be less than 1%, substitution in Equation 36 gives $R_L >$ 8150 megohms.

Since "Stabelex D" capacitors have a self-time constant of 1×10^6 seconds at 30°C, the equivalent leakage resistance for a 20 microfarad capacitor will be 50,000 megohms. Therefore the "Stabelex D" capacitor will be satisfactory from the standpoint of leakage resistance.

Since the temperature change in capacitance is 0.01%/°C, for a temperature change of 20°C the change in capacitance will be 0.2% which will contribute little to the final computer error.

The dielectric adsorption of the capacitor will result in an error of 0.1% of the drill hole volume represented by the fully charged capacitor. Although this error cumulates as the capacitor makes a number of excursions between its maximum voltage and zero, the per cent error in the total volume will still be 0.1% since the incremental volumes are also cumulated.

F. THE CURRENT CONTROLLER

The maximum current output of the current controller circuit is given by Equation 20:

$$i_{max} = \pi \alpha_3 C r^2_{max} \frac{(dx)}{(dt)max} \qquad \text{........(20}$$

Since the following factors have been previously determined,

$$\alpha_3 = 0.6 \text{ volts/ft}^3 \qquad \frac{(dx)}{(dt)max} = 2.5 \text{ ft/sec.}$$

$$r_{max} = 1.25 \text{ ft.} \qquad C = 21.5 \times 10^{-6} \text{ farads}$$

substitution in Equation 20 gives:

$$i_{max} = 158.3 \text{ microamperes}$$

Knowledge of i_{max} permits the value of the controller tube cathode resistor R_k to be determined. Referring to Figure 4, the current controller tube operates similar to a cathode follower and thus the voltage appearing across the cathode resistor is approximately equal to the voltage appearing between the controller tube grid and the lower end of the cathode resistor. The lower end of R_k is connected to a tap on potentiometer P_4 which is located at a point such that three-quarters of the total resistance appears between the tap and the upper end of the potentiometer and therefore the maximum voltage applied to the grid of the tube is $3 \frac{E_B}{4}$. Since this voltage will be approximately equal to the

voltage drop across R_k,

$$\frac{3 E_B}{4} = i_{max} R_k.$$

If we choose E_B = 90 volts, then $R_k = 4.27 \times 10^5$ ohms. Since R_k is not critical, 4.0×10^5 ohms will be satisfactory and will permit a current flow which is slightly greater than the maximum required.

If the integrating capacitor is to charge to 300 volts, the current controller plate supply voltage E_p must be somewhat greater than this voltage plus the screen to cathode voltage E_{sg}. E_{sg} is not critical and if it is set at 45 volts, E_p must be greater than 345 volts. Setting E_p equal to approximately 400 volts will ensure satisfactory performance.

G. SPECIFICATION OF RESISTOR R_3

Referring to Figure 4 and as discussed in Section III C, Subsection iii, the servo amplifier 2 controls the current controller output current i such that:

$$E_{slp} = i R_3 \qquad \text{........(8}$$

From Equation 16, R_3 is given by:

$$R_3 = \frac{\alpha_1^2 \alpha_2 \beta_1}{\pi \alpha_3 C \theta^2 max} \qquad \text{........(38}$$

The following factors have been defined previously:

α_1 = 280 degrees/foot $\qquad$ $\beta_1 = 0.1647 \times 10^{-2}$ volt sec/degree

α_2 = 1080 degrees/foot $\qquad$ $C = 21.5 \times 10^{-6}$ farads

α_3 = 0.6 volts/ft^3 $\qquad$ θ_{max} = 350 degrees

and substitution in Equation 38 gives:

$$R_3 = 2.815 \times 10^4 \text{ ohms.}$$

The maximum signal source impedance seen by servo amplifier 2 will be equal to R_3 plus the maximum resistance of the square law potentiometer or approximately 40 thousand ohms. This large impedance suggests that if a standard Brown servo amplifier is to be used, an impedance changing preamplifier might be required.

By reducing the magnitude of the transfer function β_1, it is possible to reduce the size of R_3, making a preamplifier unnecessary. The factor β_1 may be reduced by the method shown in Figure 10. A resistor R_s is placed in series with the tachometer and the square law potentiometer. The voltage E_T^1 across the potentiometer is therefore:

$$E_T^1 = \frac{R_2}{R_s + R_2} E_T$$

from which:

$$\beta_1^1 = \frac{E_T'}{\omega} = \frac{R_2}{R_s + R_2} \frac{E_T}{\omega} = \frac{R_2}{R_s + R_2} \beta_1$$

If $R_s = 100{,}000$ ohms, and since $R_2 = 9{,}867$ ohms,

$$\beta_1^1 = 0.08981\ \beta_1 = 0.1479 \times 10^{-3}.$$

Substituting the same factors in Equation 38 but using β_1^1 instead of β_1,

$$R_3 = 2{,}528 \text{ ohms}$$

The maximum signal source impedance will now be approximately 13,000 ohms, which permits the use of the Brown servo amplifier directly.

The maximum input voltage to servo amplifier 2 will be given by:

$$i_{max} R_3 = 158.0 \times 10^{-6} \times 2528 = 0.3994 \text{ volts}$$

A signal of this magnitude may be accepted directly by the Brown servo amplifier.

V. LABORATORY TEST OF THE COMPUTER

The laboratory tests of the computer which are described below comprise an investigation of the performance of individual computing elements and an investigation of the performance of the computer as a whole.

Performance testing of the individual elements consisted of determining the accuracy of the linear-square law potentiometer combination, the leakage resistance associated with the integrating capacitor and the minimum current-controller current.

Tests of the complete computer evaluated its performance under conditions simulating actual field operation of the computer. These tests included runs simulating drill holes having different constant radii, a drill hole having a constant radius but logged at different speeds and a run which reproduced the input signals which would be obtained during logging an actual well.

A. ACCURACY OF THE LINEAR-SQUARE LAW POTENTIOMETER COMBINATION

i. Method of Investigation

The shaft rotation angle θ necessary to obtain a resistance R_1' between the output terminals of a linear potentiometer is given by:

$$\theta = \frac{R_1' \theta_{max}}{R_1} \qquad \text{........(39}$$

where R_1 = total resistance of the linear potentiometer

The resistance between the output terminals of the square law potentiometer is given by:

$$R_2' = \frac{\theta^2}{\theta_{max}^2} R_2 \qquad \text{........(40}$$

where R_2 = total resistance of square law potentiometer.

Both potentiometers are driven by the same shaft and their sliders are phased such that the resistance between the output terminals of each potentiometer is zero when $\theta = 0$. If the slider of the linear potentiometer is adjusted so that the resistance between its output terminals is equal to R_1', the resistance between the output terminals of the square law potentiometer is given by:

$$R_2' = \frac{R_1'^2}{R_1^2} R_2 \qquad \ldots\ldots\ldots(41$$

Equation 41 may be applied in testing the linear-square law potentiometer combination as follows.

1) The total resistance of each potentiometer is measured.
2) The shaft of the potentiometer combination is adjusted so that a given resistance is obtained between the output terminals of the linear potentiometer.
3) Without disturbing the shaft, the resistance between the output terminals of the square law potentiometer is measured.
4) The resistance which would have been measured in Step 3 if the potentiometers had no errors is calculated from Equation 41.
5) The error of the combination for the given setting is given by the difference between the measured resistance and the calculated (correct) resistance.
6) The above procedure is repeated at a number of points covering the range of the potentiometers.

ii. Results

The error in the output of the linear-square law potentiometer combination used in the computer is shown in Figure 11. Also shown for comparison are curves of the theoretical limiting and probable errors

as calculated from Equations 32 and 33 for potentiometer tolerances of 0.5%. The tachometer term is not included in the latter calculations.

It will be seen from Figure 11 that the error in the output of the potentiometer combination is greater than 5% for a range of $3.6 < r_{max}/r < 5.0$. If r_{max} equals 15 inches, the corresponding drill hole radius range is $3" < r < 4.2"$. This performance is not entirely satisfactory since as noted in a previous section, a drill hole having a radius of 3.75 inches might be met in practice, and for sections having this radius, the error in the computer output due to the potentiometer inaccuracies alone would be greater than 5%. If the drill hole radius is greater than 4.2 inches, however, (and this would normally be the case) the potentiometer contribution to the total error would be less than 5% and therefore for the development model of the drill hole volume computer, the 0.5% tolerance potentiometers are considered satisfactory.

In order to reduce the error due to the potentiometers chosen for the development model, the following remedial measures could be taken:

a) The value of r_{max} could be reduced to 12.5 inches. This would permit a drill hole having a minimum radius of 3.5 inches to be logged with a potentiometer error contribution of less than 5%.

b) The phasing of the potentiometer sliders could be adjusted so as to reduce the error in the region $r_{max}/r = 4$. This adjustment would be made at the expense of accuracy in other regions of r_{max}/r.

The above measures are merely means of circumventing the correct solution to the problem which is to use potentiometers having

lower tolerances. Potentiometers having 0.2% tolerance would probably afford satisfactory performance.

It is interesting to note in Figure 11 that the observed error for the potentiometer combination is considerably lower than the theoretical limiting error. Thus it appears that a design based upon the concept of a theoretical limiting error would be too conservative. The observed error exceeds the theoretical probable error in some regions, however, and a design based upon the latter concept would appear to have an inadequate factor of safety. Reference 16 suggests that results obtained from the probable error theory may be expected to be correct within a factor of two. For the analysis of the performance of the linear-square law potentiometer combination, this has been verified.

B. LEAKAGE RESISTANCE ASSOCIATED WITH THE INTEGRATING CAPACITOR

1. Method of Investigation

Leakage of charge from the integrating capacitor may occur through the following paths (See Figure B-1, Appendix B):

1. The internal leakage resistance of the capacitor
2. Vacuum tube voltmeter grid current
3. Through the current-controller and vacuum tube voltmeter tube bases and sockets to ground
4. Through the discharge relay contact insulation
5. Through the current-controller grid voltage potentiometer to the servo motor to ground.

The equivalent capacitor leakage resistance resulting from the parallel combination of these paths must be higher than the minimum allowable leakage resistance of 8150 megohms specified in Section IV-E.

The equivalent leakage resistance can be determined by charging

the integrating capacitor and reading the decline in voltage as a function of time. A simple graphical analysis of these data permits the leakage resistance to be obtained.

In performing the test, the current-controller plate voltage was removed, thus ensuring that no charge would leak onto the capacitor. The capacitor voltage was measured indirectly by measuring the voltage at the cathode of the computer vacuum tube voltmeter tube (see Appendix B and Figure B-1).

ii. Results

The results of the first leakage test performed upon the capacitor and the associated components are given in Table III. The leakage resistance was found to be 4000 megohms. Since this was lower than the minimum value acceptable, it was evident that the system required improvement in this regard. The most likely source of leakage was thought to be through the current- controller grid potentiometer and therefore a polystyrene coupling between the potentiometer shaft and the motor was fabricated and a second test performed. The results of this test are contained in Table IV. These data gave a leakage resistance of 13,200 megohms. Since this met the requirements of the integrating circuit, no further attempts to improve the leakage characteristics were made.

C. RESIDUAL CURRENT-CONTROLLER CURRENT

i. Method of Investigation

The residual current-controller current was determined indirectly by measuring the rate of voltage rise on the initially uncharged integrating capacitor. A simple graphical analysis of the results permits the current entering the capacitor to be obtained. For this test, all external connections to the capacitor excepting the

current-controller were removed, thus minimizing any errors which might result due to external leakage. The voltage decline due to the self time constant of the capacitor was not measureable over a period of time comparable to that used for the test. Measurements of the capacitor voltage were made with a General Radio Company Type 1800-A vacuum tube meter which has an input impedance of several thousand megohms. The meter was attached to the capacitor only while a measurement was being made.

ii. Results

The results of the residual current measurements are given in Table V. The minimum residual current was found to be 0.082×10^{-6} amperes.

From Equation 37, the maximum residual controller current is given by:

$$i_{res} = \frac{p\, C\, E_{C\,max}}{t_s} \qquad \ldots\ldots\ldots(37)$$

where: C = integrating capacitor capacitance

p = allowable fractional error due to i_{res}

$E_{C\,max}$ = maximum integrating capacitor voltage

t_s = period of time during which logging may be halted for a fractional error less than p.

For a current of 0.082×10^{-6} amperes, $p = .01$, $E_{C\,max} = 300$ volts and $C = 21.5$ mfd, the maximum permissable period over which logging may be stopped is 790 seconds or 13 minutes. Thus reasonably long interruptions in logging per charge cycle of the integrating capacitor may occur without requiring the application of corrections to the final record.

D. OPERATING CHARACTERISTICS OF THE COMPLETE COMPUTER

i. Method of Investigation

The operating characteristics of the complete computer were obtained by simulating the input signals which the computer would receive during the logging of a well. These signals were fed to the computer and the computer output recorded. A record of the radius input signal permitted calculation of the volume simulated and by comparing this with the computer output volume, a measure of the accuracy of the computer was obtained.

The details of the simulation system are presented in Figure 12. The main part of the system is a dual pen strip chart recorder. The chart roller transports a chart upon which has been previously plotted the drill hole radius curve which is to be simulated by the system. The output of the computer is recorded as a function of depth on the same chart. The chart roller is driven by a synchronous motor through a system of gears. A direct mechanical connection is made between the recorder chart motor and the computer tachometer, the output of which is fed to the square law potentiometer in the computer. The chart motor is powered by a power amplifier and an audio oscillator. The speed of the chart motor is therefore controlled by the frequency generated by the oscillator and thus changing the latter permits changes in logging velocity to be simulated. The output voltage from a potentiometer battery combination is fed to the computer and also to the 'radius' pen of the recorder. This provides the radius signal input to the computer. The computer output is fed to the 'volume' pen of the recorder.

In operation, the recorder chart motor is energized. The recorder radius pen is controlled by manually manipulating the poten-

tiometer radius input knob such that the pen follows the radius curve plotted on the chart. This provides a voltage input to the computer which is proportional to the radius plotted on the chart. The radius pen records its deflection on the chart and thus if the plotted curve is not followed exactly, the recorded curve can be used for calculating the simulated volume. To simulate changes in the logging velocity, the frequency of the oscillator can be changed arbitrarily during the course of a run. This will change the speed of the tachometer and recorder chart proportionately.

To apply the system shown in Figure 12, it is necessary to determine the scale factor α_2. The remaining scale factors and transfer functions remain as previously determined.

The scale factor α_2 is defined as:

$$\alpha_2 = \frac{\text{Tachometer shaft angular velocity, ft/sec}}{\text{Rate of logging, ft/sec}} = \frac{\omega}{\frac{dx}{dt}}$$

With an input frequency of 60 cps, the angular velocity of the chart motor is 180 rpm or 1080 degrees/sec and the linear travel of the recorder chart is one inch in 7.5 seconds. If the desired radius curve is plotted such that one inch of chart travel represents 15 feet of drill hole depth, the equivalent logging velocity is 2 ft/sec. and thus α_2 = 540 degrees/ft. The factor α_2 determines the size of resistor R_3 as given by Equation 38. Resistor R_3 was previously determined as 2528 ohms with α_2 = 1080 degrees/ft. With α_2 = 540 degrees/ft, R_3 becomes 1264 ohms.

With this one change, the system depicted in Figure 12 may be used with the computer design as previously determined to evaluate the operating characteristics of the computer as a whole. Figure 13 is a collection of photographs showing the apparatus used in testing the complete computer.

ii. Results

The error performance of the complete computer was determined by running three separate tests. The first test determined the computer error in logging at a constant velocity ideal drill holes having different constant radii. The second test determined the computer error due to changes in logging velocity while the third test was a run simulating the type of radius signal which would be encountered in logging an actual drill hole. The results of these tests will be discussed separately below.

a. The constant radius drill hole test

The constant radius test comprised a series of runs simulating drill holes having different constant radii of 3 through 10 inches, with the radius for each successive test increasing by one inch. To eliminate the effect of any tachometer non-linearity, these runs were made at a constant logging velocity equivalent to 120 feet per minute. For a given radius, the run was continued until the computer indicated a volume of 250 cubic feet at which point the run was terminated. The number of feet of hole necessary to obtain this volume was read from the recorder chart and the actual volume of a hole of this depth was calculated. The difference between this volume and the computed volume of 250 cubic feet gave the computer error at the given radius.

The recorder chart from the constant radius test is reproduced in Figure 14 while the results of the test are given in Table VI. It will be noted that the radius scale of Figure 14 covers a range of 0 to 10 inches. This scale was chosen for convenience, the computer being calibrated for a maximum radius of 15 inches as discussed earlier. The stepped appearance of the volume curve is caused by the

limited resolution of the recorder and is not a characteristic of the computer output.

Table VI shows that the computer error varied from 8.15% for a radius of 3 inches to -2.27% for a radius of 10 inches, the negative error indicating that the computer volume was smaller than the true volume of the hole. The computer error given in Table VI is plotted on Figure 15 as a function of r_{max}/r . The observed error of the linear-square law potentiometer combination is plotted on the same figure.

It will be noted that for r_{max}/r less than 3.75, the curves have approximately the same slope, indicating that the error of the computer is primarily governed by the errors of the potentiometers. The computer curve is lower than the potentiometer error curve however, suggesting that there is a consistent error in the computer. This is probably due to one or more small errors in the calibration of the computer but its cause was not sought since it was thought that the computer error performance as shown on Figure 15 was satisfactory.

For $r_{max}/r = 5$ ($r = 3$ inches), the computer error is some 3% higher than the potentiometer error. The reason for this behavior could not be determined. It was conclusively proven by experiment and also by the application of Equation 35 that the error was not due to leakage of charge from the integrating capacitor, although this would cause a deviation in the correct direction.

b. The variable logging velocity test

Figure 16 and Table VII present the results of the test which determined the computer error due to variations in logging velocity. The curves were obtained for a constant radius of 7 inches

while the equivalent logging velocity was varied from 42.5 to 195 feet per minute. During a run, the logging velocity was maintained at a constant value until the computer registered a volume of 250 cubic feet. The number of feet of hole necessary to obtain this volume at the given rate of logging was read from the chart and a run at a different velocity was made. The difference between the drill hole depth for the two cases was taken as a measure of the computer error. To compare the computer error at various rates, the error at a logging velocity of 156 feet per minute was arbitrarily assumed zero. The latter velocity is the maximum which would be used in practice and is also the approximate velocity at which logging is normally conducted.

From Table VII, it is seen that the computer error is largest at the lowest logging velocity. Furthermore, the error is in a direction such that the computer volume is too large at lower velocities. This is a consequence of the slightly drooping output voltage characteristic of the tachometer. The computer error of 2.2% at a velocity of 42.5 ft/minute is consistent with the observed linearity of the tachometer of 0.5%.

c. The simulated drill hole logging test

This test was devised to check the overall performance of the computer under conditions which would be met during logging an actual drill hole. In particular it tests the ability of the computer servo mechanisms to follow their respective varying input quantities, the steady state computing errors having been evaluated by the previous tests.

To provide the radius input signal, the system shown in Figure 12 and discussed earlier was used. The drill hole radius curve which was plotted on the recorder chart was obtained from a caliper survey which had been run on Imperial Cynthia No. 3-1-52-11-W5 on April 2nd, 1954. The interval plotted on the chart corresponded to a 1000 foot section of the well between the depths of 4100 to 5100 feet KB.

The equivalent logging velocity was not varied during the test since changes in logging velocity in the field do not occur rapidly, the time variation of the drill hole radius placing far more stringent requirements on the performance of the servo mechanisms.

The performance of the computer was evaluated by comparing the drill hole volume as given by the computer to the calculated volume of the drill hole. The latter was obtained as follows. The radius curve plotted by the recorder pen was divided into sections of 100 feet. The average drill hole radius for every five feet of each section was carefully estimated by inspection. The volume of each of the five foot increments was then calculated and these volumes were summed to obtain the volume of the 100 foot section. To serve as a control for the estimation of the average radius of the five foot sections, the average radius ordinate for each 100 foot section was obtained by planimetering the recorded radius curve. The average planimeter ordinate was compared to the average of the twenty estimated radius ordinates. If these figures differed by more than 0.2%, the radii of the five foot sections were re-estimated and the check was repeated. The manually plotted radius curve was not used for these calculations since it was possible to follow this curve exactly with the recorder radius pen.

Figure 17 is a reproduction of the recorder chart obtained from the test. The results of the test are tabulated in Table VIII. It will be seen from the table that the computer error for this test varied from 1.24 to 1.87%. The average radius of the 1000 foot interval is approximately 6.9 inches and from Figure 15 it is seen that the static computer error for this radius is approximately 1.4%. Thus it may be concluded that since the computer error from the simulated drill hole test is approximately the same as the inherent static computer error, the computer was operating in a satisfactory manner during the test.

VI. CONCLUSIONS AND RECOMMENDATIONS

An electric analog computer for obtaining a curve of the volume of an oilwell drill hole as a function of depth has been designed, developed and tested in the laboratory.

The theoretical analysis of the design has shown that the computer could be constructed so as to be accurate to within one or two percent. Tests of the development model of the computer showed it to be accurate to within five percent for drill holes greater than four inches in radius.

Throughout the laboratory tests the computer was found to be trouble free and stable with respect to maintaining calibration.

A full evaluation of the operating characteristics of the computer should be made under field conditions. For such a series of tests, the following suggestions are made.

a. The linear and square law potentiometers used in the

development model should be replaced with units having a tolerance of 0.2% or better. This would effect an improvement in the accuracy of the computer which would result in a better indication of its capabilities.

b. The possibility of obtaining a more precise tachometer should be investigated. This should result in improved performance at lower logging velocities.

c. The most likely source of difficulty in maintaining the performance of the computer in the field is thought to be preserving the insulation resistance of those portions of the computer which are connected to the integrating capacitor. Frequent leakage tests should be made in the field in order to evaluate this factor.

TABLE III

Determination of Leakage Resistance of Integrating Capacitor and Associated Components

Time-t Minutes	Seconds	Capacitor Voltage-V_t
0	0	291.0
11 1/2	690	288.9
29	1740	285.3
38	2280	283.8
46	2760	282.0
54	3240	280.5
60	3600	279.6
66 1/2	3990	278.1

Data may be fitted approximately by:

$$V_t = V_o e^{-\frac{t}{RC}}$$

where RC = 87,000 seconds

V_o = 291.0

C = 21.5 mfd

thus R = 4000 megohms

TABLE IV

Determination of Leakage Resistance of Integrating Capacitor and Associated Components
Servo Motor No. 2 Isolated

Time -t Minutes	Seconds	Capacitor Voltage-V_t
0	0	292.5
6	360	291.9
11 1/2	690	291.6
16	960	291.3
25	1500	290.7
40	2400	289.8
53	3180	289.0
73	4380	287.8

For these data:

RC = 283,000 seconds

V_o = 292.5

R = 13,200 megohms

TABLE V

Determination of Minimum Current-Controller Current

Time - t Seconds	Voltage - V
0	0
30	0.10
60	0.23
90	0.34
120	0.46
150	0.56
180	0.70
240	0.93
300	1.15

These data may be fitted approximately by:

$$V = \frac{i}{C} t$$

where $i/C \cong 0.00382$ volts/second

Since $C = 21.5$ mfd,

$i = 0.082 \times 10^{-6}$ amperes

TABLE VI

Computer Error for Constant Radius Drill Hole

Logging velocity 120 ft/minute

Data taken from Figure 14

Drill Hole Radius	Observed Hole Depth for Indicated Volume of 250 ft^3	True Volume of Hole	Percent Computer Error $\frac{(\text{Indicated} - \text{True Volume})}{.01 \times \text{True Volume}}$
3 inches	1177.25 ft	231.25 ft^3	8.15 %
4	681.75	237.98	5.05
5	456.75	249.12	0.35
6	320.0	251.33	-0.53
7	237.5	253.89	-1.53
8	183.5	256.21	-2.42
9	145.0	256.24	-2.44
10	117.25	255.80	-2.27

TABLE VII

Computer Error Due to Variation in Logging Velocity

Drill hole radius 7 inches

Data taken from Figure 16

Computer error assumed zero at
logging velocity of 156 ft/min

Logging Velocity	Observed Hole Depth for Indicated Volume of 250 ft^3	Relative Depth Deviation	Relative Volume Error	Relative Percent Error
42.5 ft/min	232.62 ft	5.13 ft	5.49	2.20 %
81	235.63	2.12	2.27	0.91
120	237.25	0.5	0.53	0.21
156	237.5	0.0	0.0	0.0
195	238.0	-0.25	-0.27	-0.11

TABLE VIII

Computer Error for Simulated Logging Run

Logging velocity = 120 ft/minute

Data taken from Figure 17

Depth Interval	Average Planimeter Radius Ordinate Over Interval	Average Estimated Radius Ordinate Over Interval*	Calculated Volume of Interval**	Cumulative Calculated Volume	Cumulative Computer Volume	Percent Computer Error
0-100 ft	7.591 inches	7.596 inches	125.93 ft^3	125.93 ft^3	124 ft^3	1.53 %
100-200	7.477	7.474	121.94	247.87	244	1.56
200-300	7.466	7.473	121.94	369.81	364	1.57
300-400	7.155	7.162	112.16	481.97	476	1.24
400-500	6.961	6.967	106.57	588.54	577.5	1.87
500-600	6.223	6.224	84.59	673.13	662	1.65
600-700	6.338	6.336	87.66	760.79	748	1.68
700-800	6.288	6.296	86.52	847.31	835	1.45
800-900	6.420	6.412	89.82	937.13	925	1.29
900-1000	6.743	6.752	99.56	1036.69	1022	1.42

* Obtained from average of estimated radius for twenty consecutive five foot sections of the interval

** Summation over the 100 foot interval of π(estimated radius for five foot section)^2

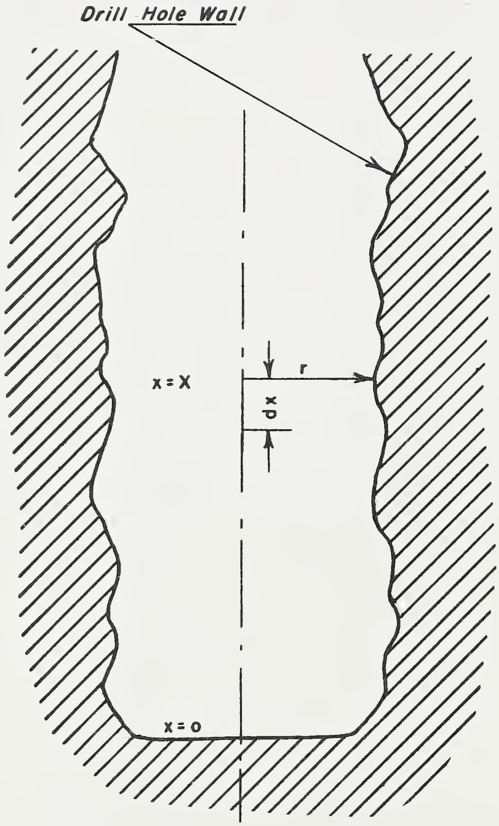
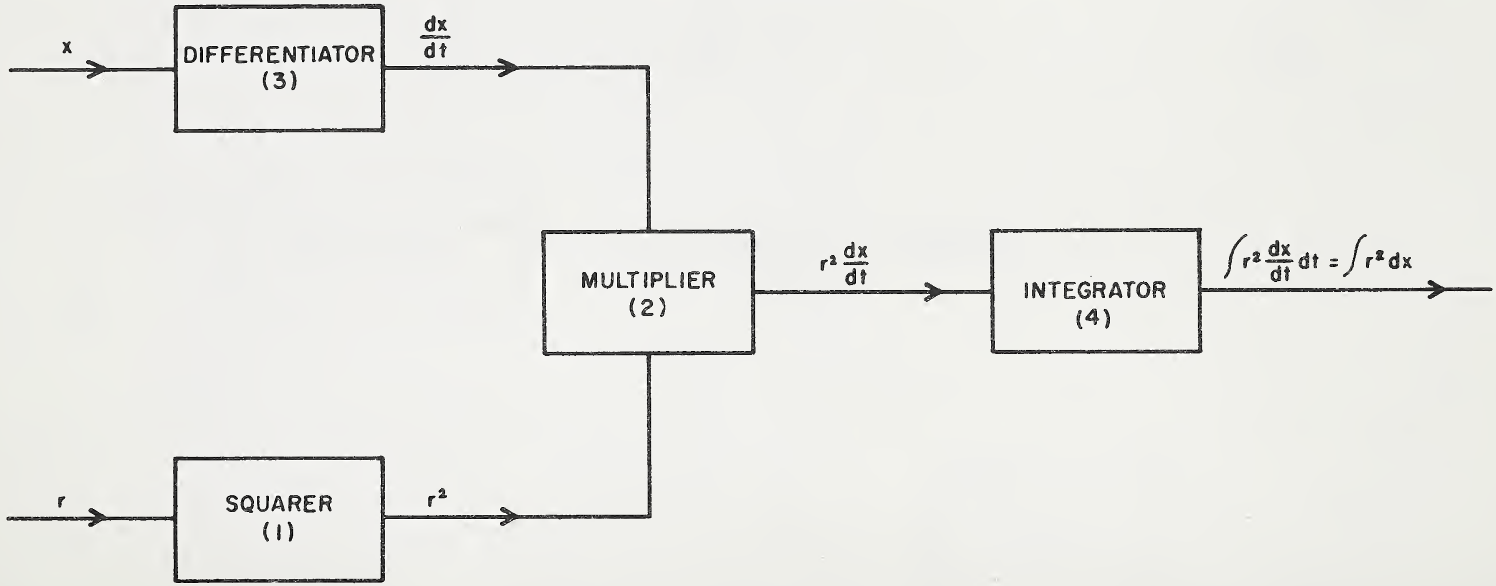
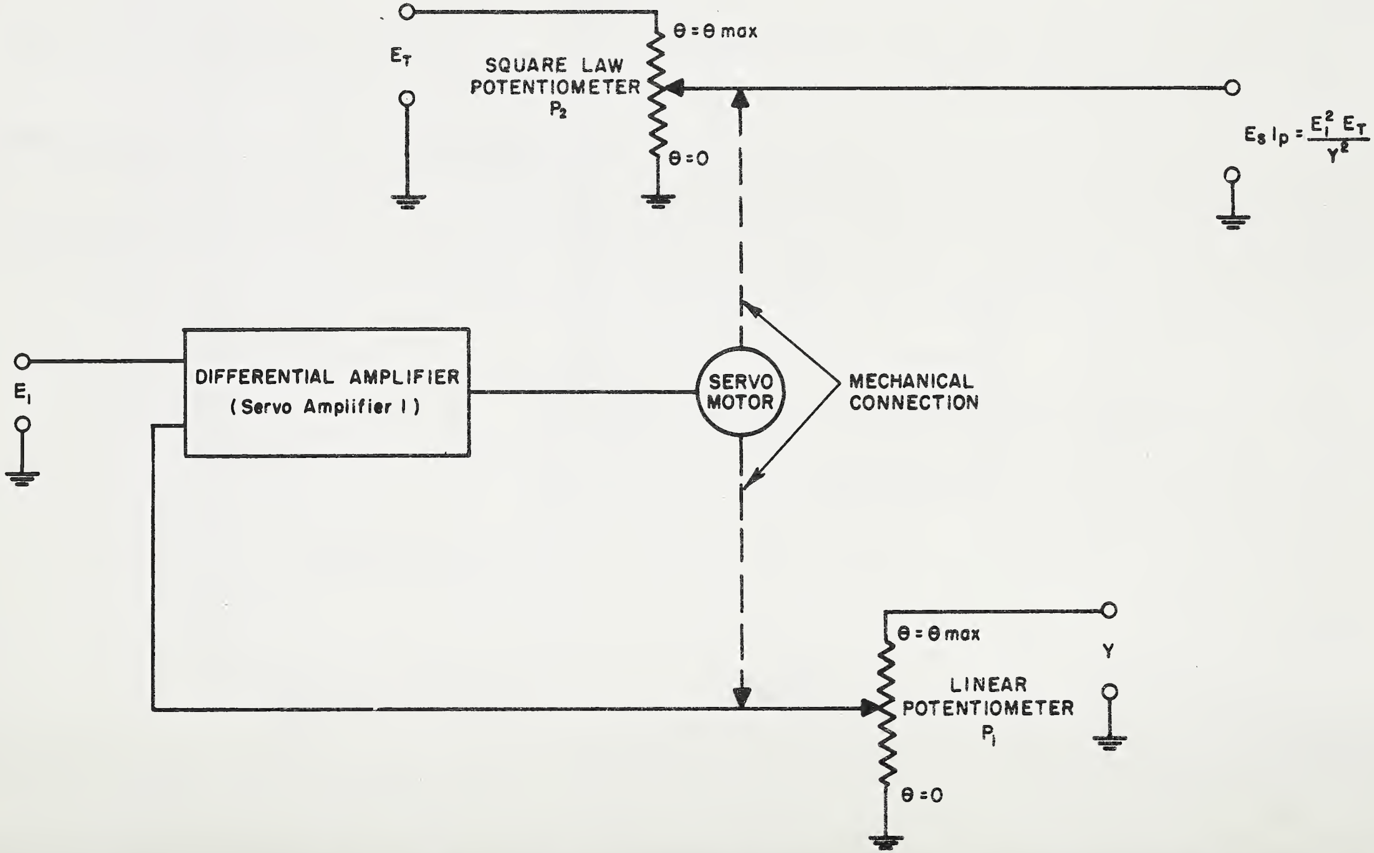


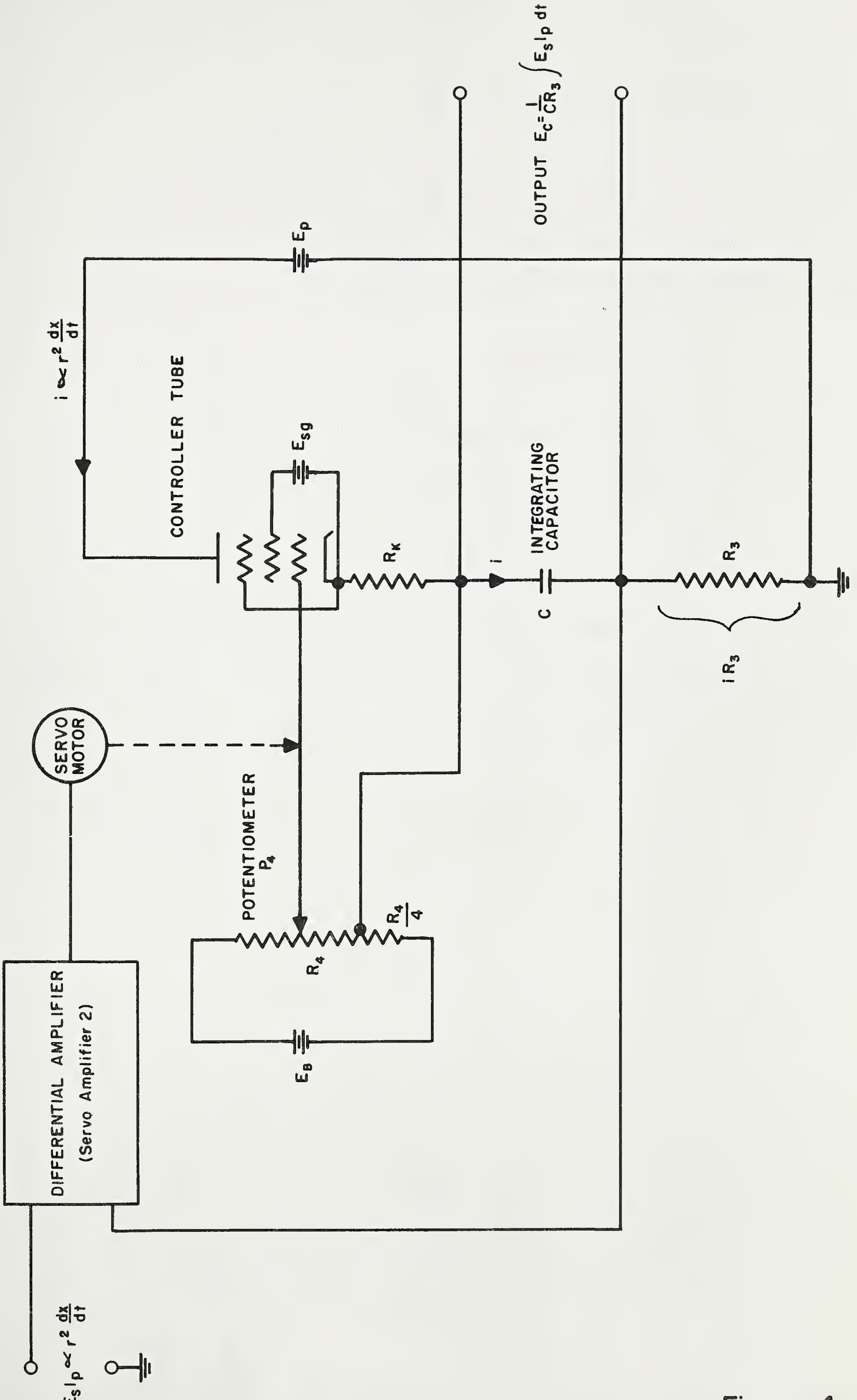
Figure 1

SECTION OF A DRILL HOLE


x
DIFFERENTIATOR
(3)
dx/dt
r
SQUARER
(1)
r²
MULTIPLIER
(2)
r² dx/dt
INTEGRATOR
(4)
∫r² dx/dt dt = ∫r² dx

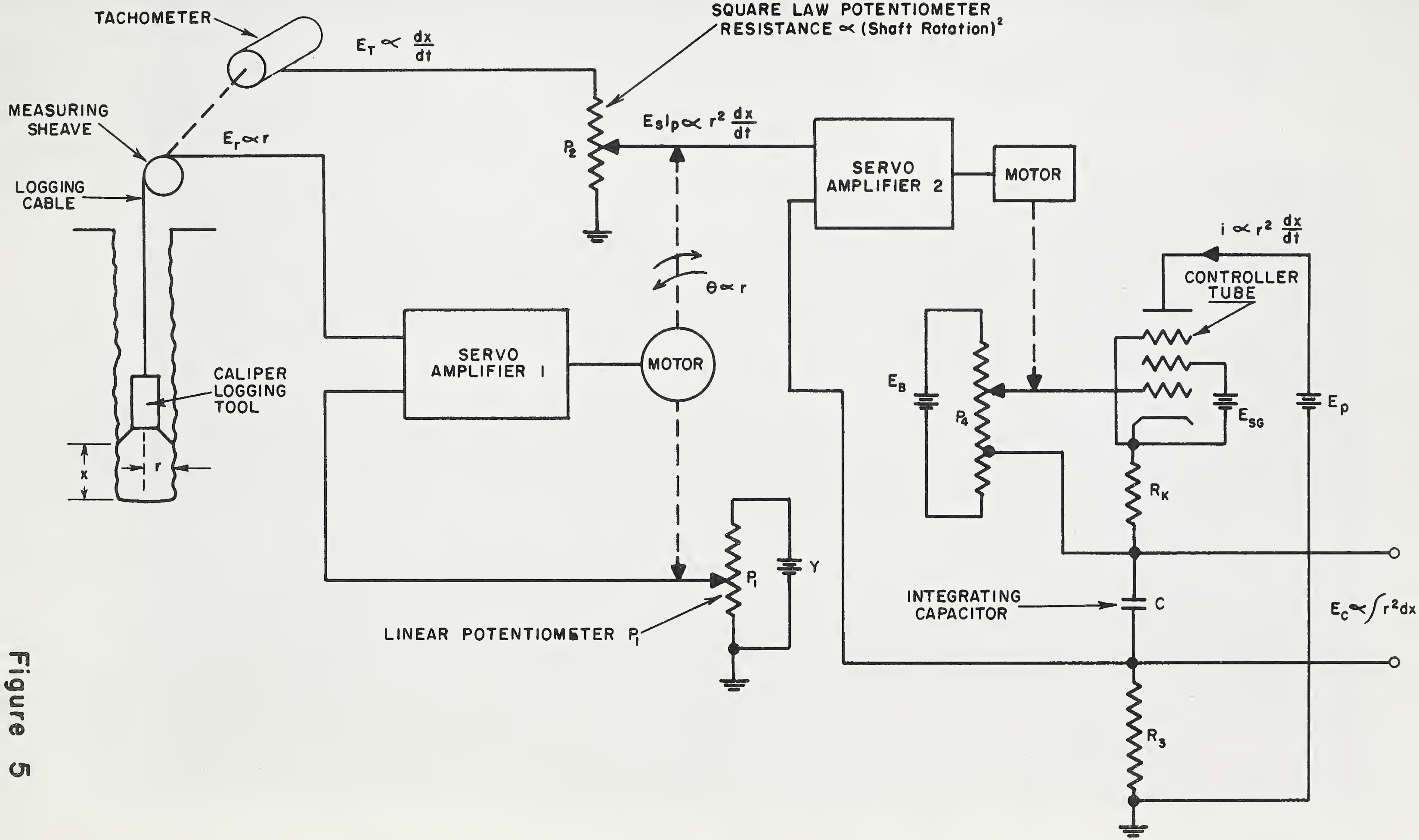

E_T
$\theta = \theta\ max$
SQUARE LAW
POTENTIOMETER
P_2
$\theta = 0$
$E_S I_P = \frac{E_1^2 E_T}{Y^2}$
E_1
DIFFERENTIAL AMPLIFIER
(Servo Amplifier I)
SERVO
MOTOR
MECHANICAL
CONNECTION
$\theta = \theta\ max$
Y
LINEAR
POTENTIOMETER
P_1
$\theta = 0$

Figure



THE INTEGRATING CIRCUIT

Figure 4



SIMPLIFIED CIRCUIT OF THE DRILL HOLE VOLUME COMPUTER

Figure 5

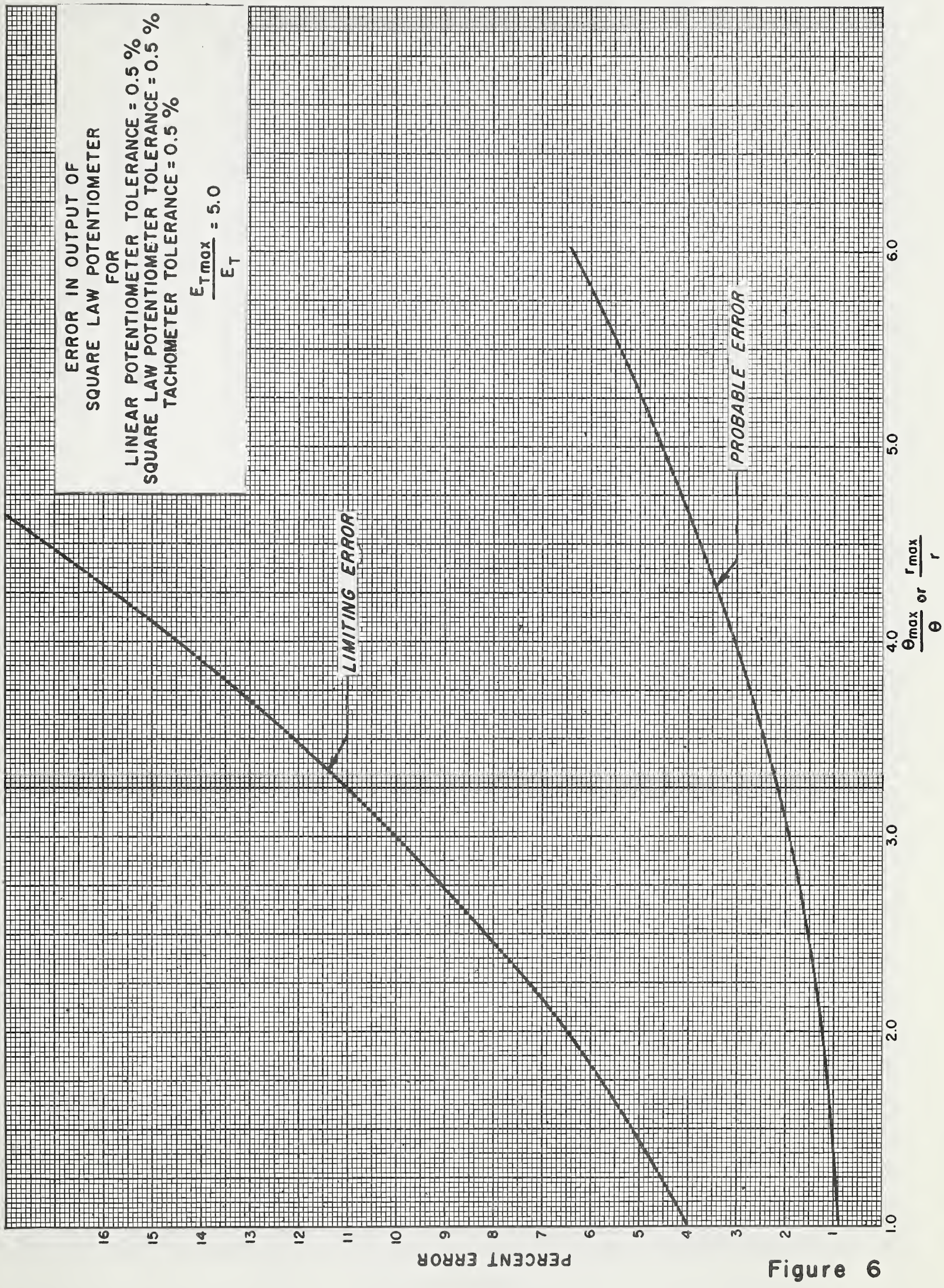

ERROR IN OUTPUT OF
SQUARE LAW POTENTIOMETER
FOR
LINEAR POTENTIOMETER TOLERANCE = 0.5 %
SQUARE LAW POTENTIOMETER TOLERANCE = 0.5 %
TACHOMETER TOLERANCE = 0.5 %
$\frac{E_{T\,max}}{E_T} = 5.0$
LIMITING ERROR
PROBABLE ERROR
PERCENT ERROR
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
1.0
2.0
3.0
4.0
5.0
6.0
$\frac{\theta_{max}}{\theta}$ or $\frac{r_{max}}{r}$

Figure 6

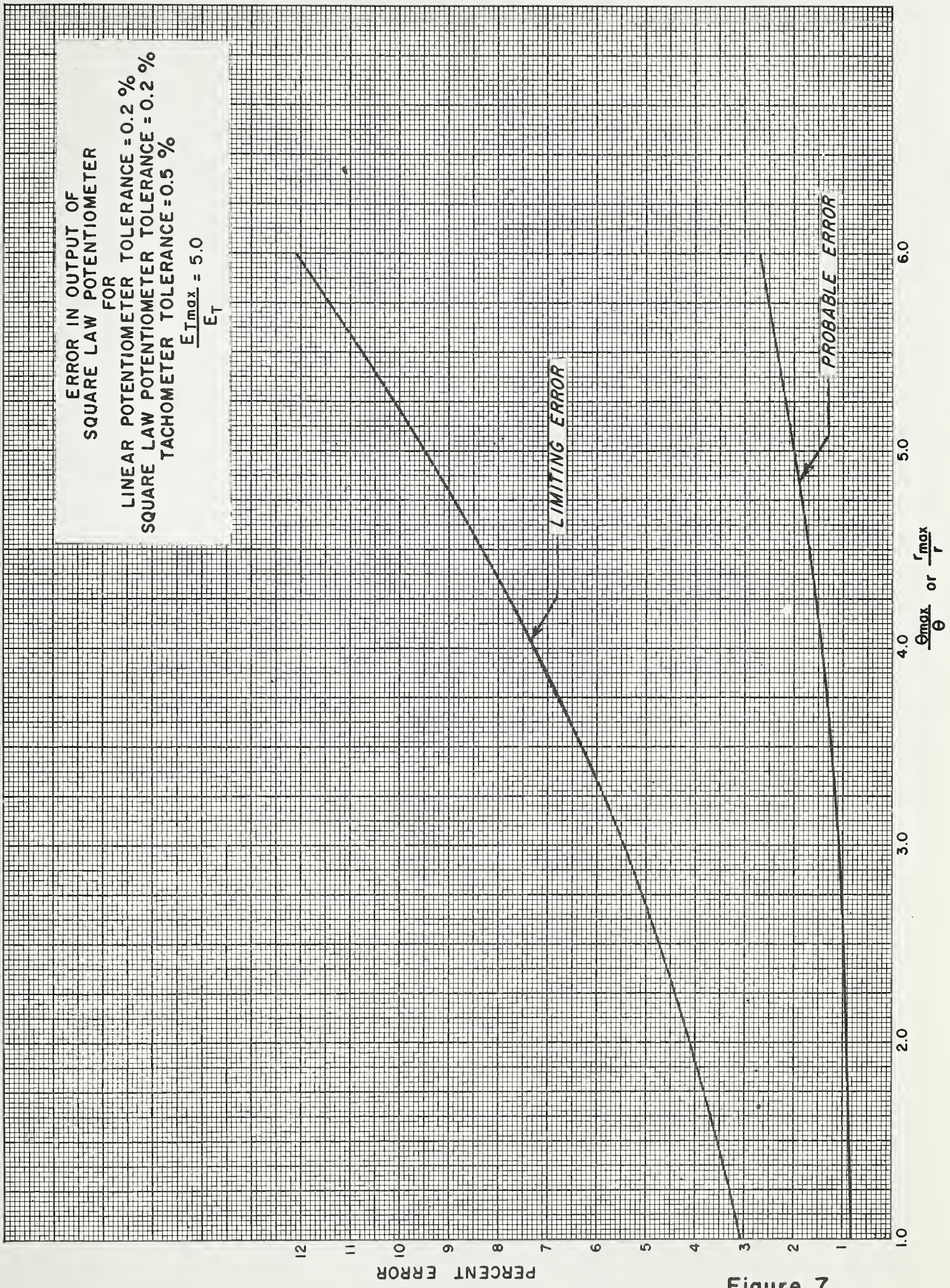

ERROR IN OUTPUT OF
SQUARE LAW POTENTIOMETER
FOR
LINEAR POTENTIOMETER TOLERANCE = 0.2 %
SQUARE LAW POTENTIOMETER TOLERANCE = 0.2 %
TACHOMETER TOLERANCE = 0.5 %
$\frac{E_{T max}}{E_T} = 5.0$
LIMITING ERROR
PROBABLE ERROR
PERCENT ERROR
1
2
3
4
5
6
7
8
9
10
11
12
1.0
2.0
3.0
4.0
5.0
6.0
$\frac{\theta_{max}}{\theta}$ or $\frac{r_{max}}{r}$

Figure 7

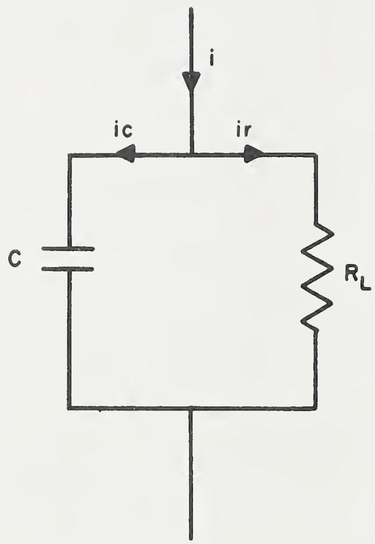


Figure 8

EQUIVALENT CIRCUIT OF THE INTEGRATING CAPACITOR

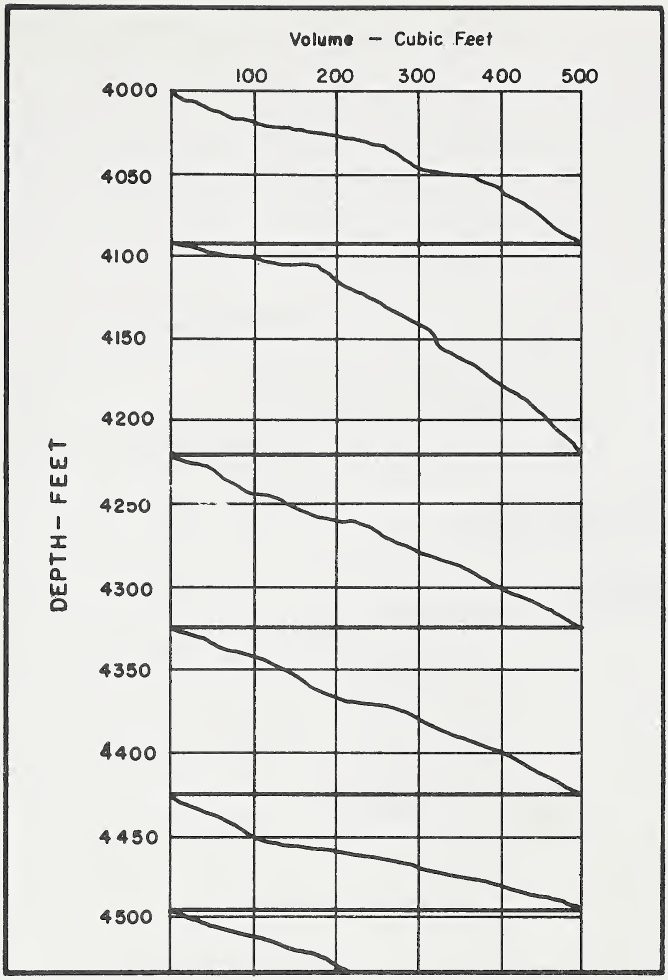


FIGURE 9

COMPUTER PRESENTATION OF DRILL HOLE VOLUME LOG

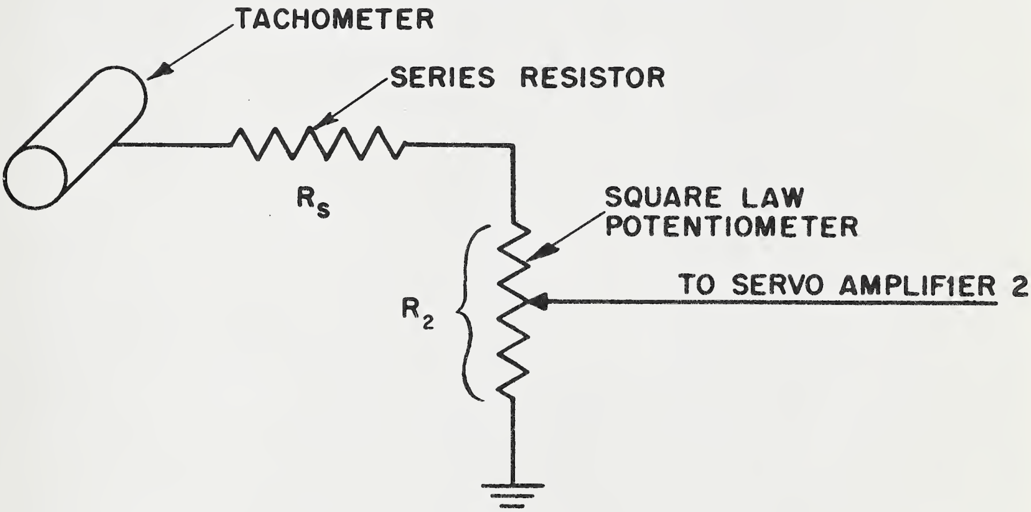


Figure 10

METHOD OF CHANGING TACHOMETER SCALE FACTOR

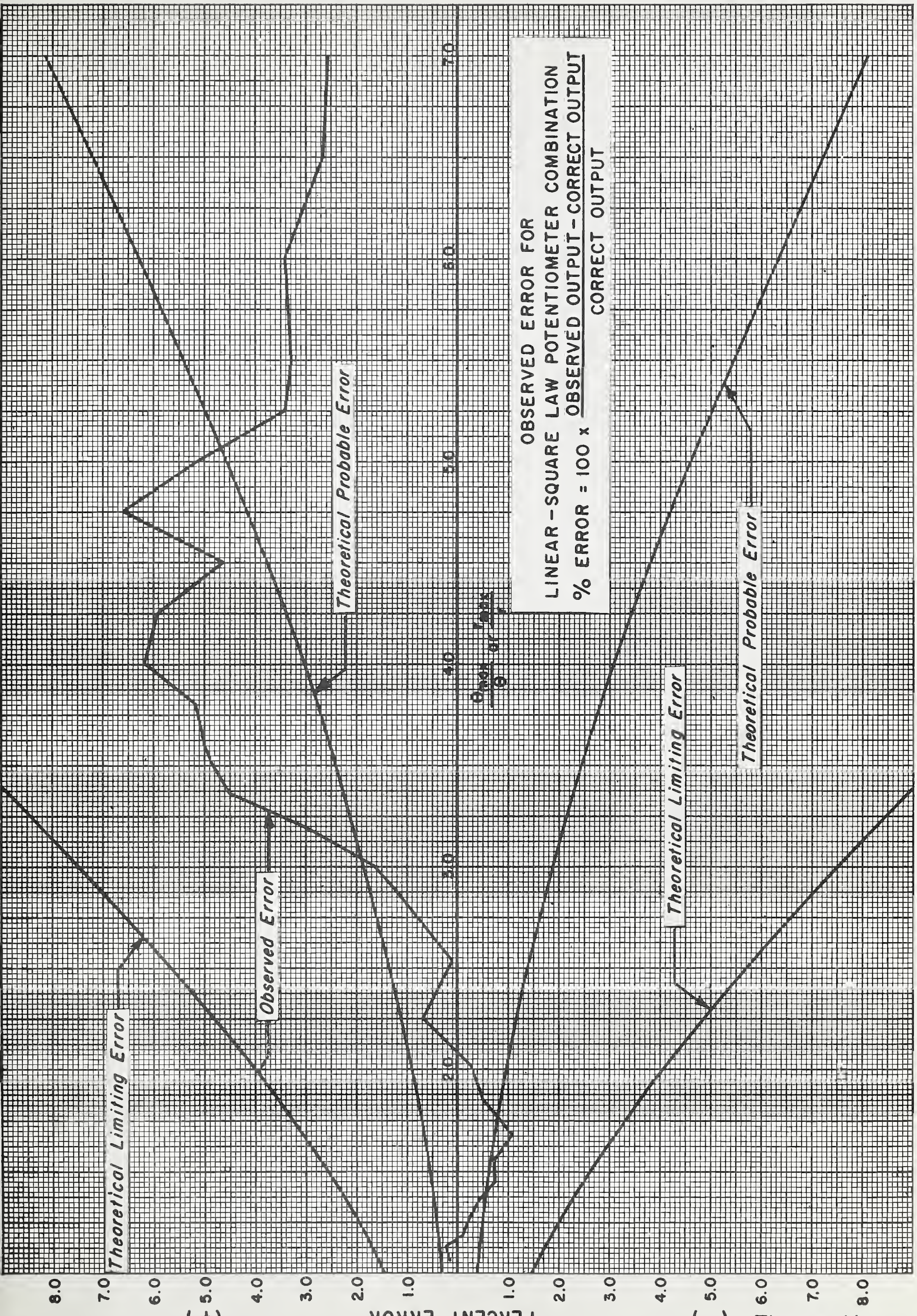
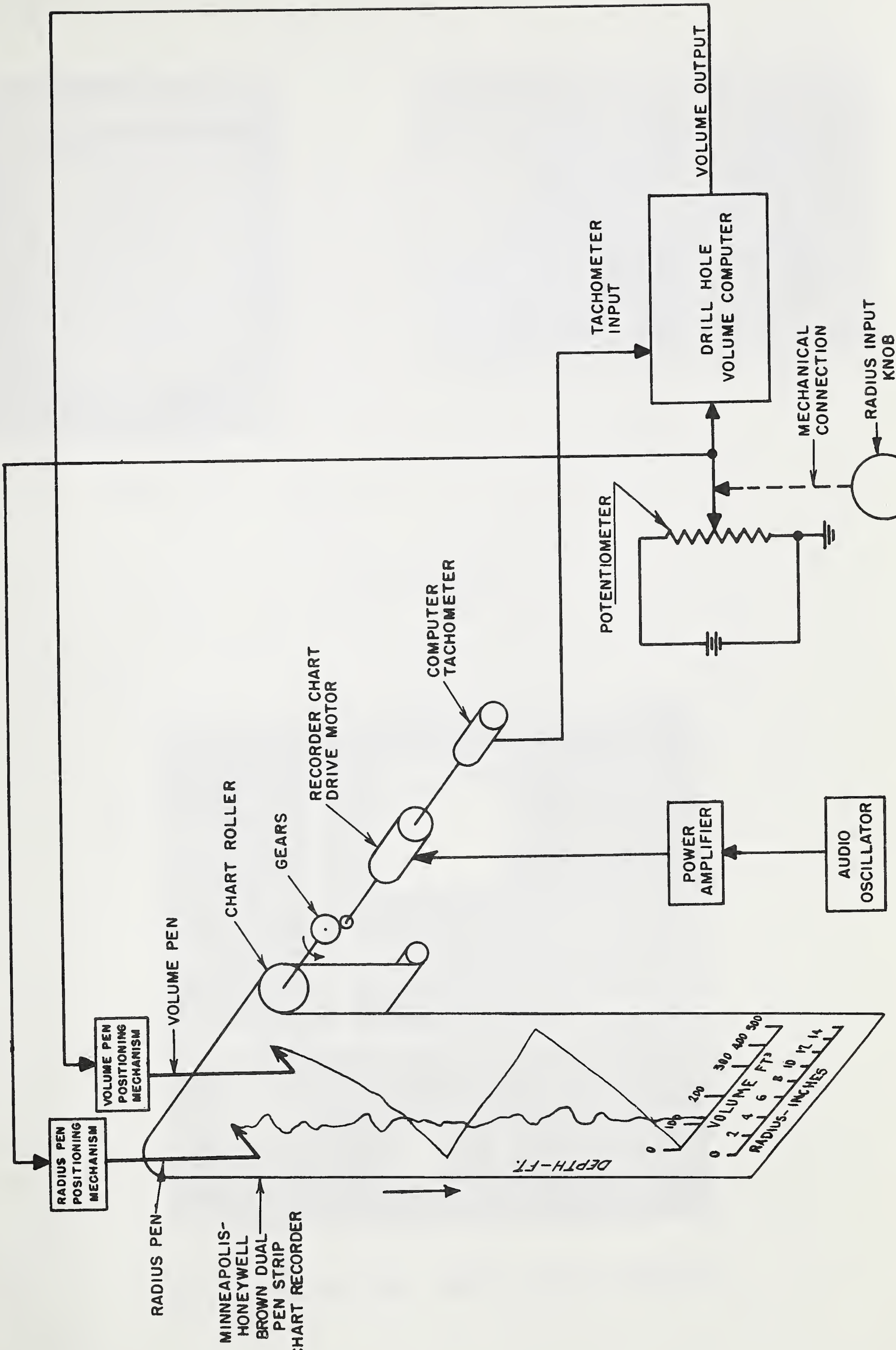
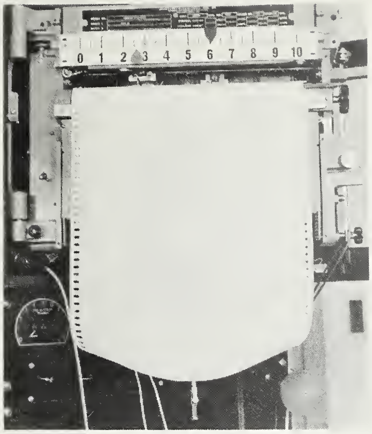

OBSERVED ERROR FOR
LINEAR-SQUARE LAW POTENTIOMETER COMBINATION
% ERROR = 100 x OBSERVED OUTPUT-CORRECT OUTPUT / CORRECT OUTPUT
Theoretical Limiting Error
Observed Error
Theoretical Probable Error
Theoretical Probable Error
Theoretical Limiting Error
2.0
3.0
4.0
5.0
6.0
7.0
PERCENT ERROR
(+)
(-)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Figure II

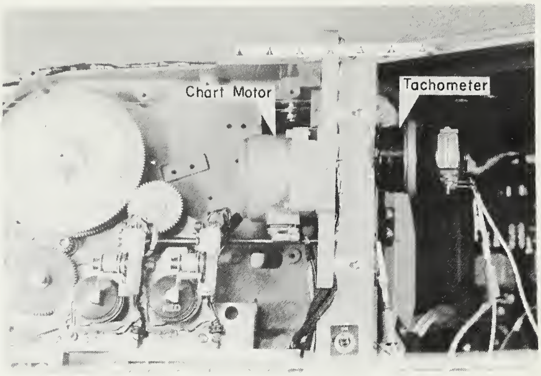


SYSTEM FOR SIMULATING DRILL HOLE LOGGING RUN

Figure 12

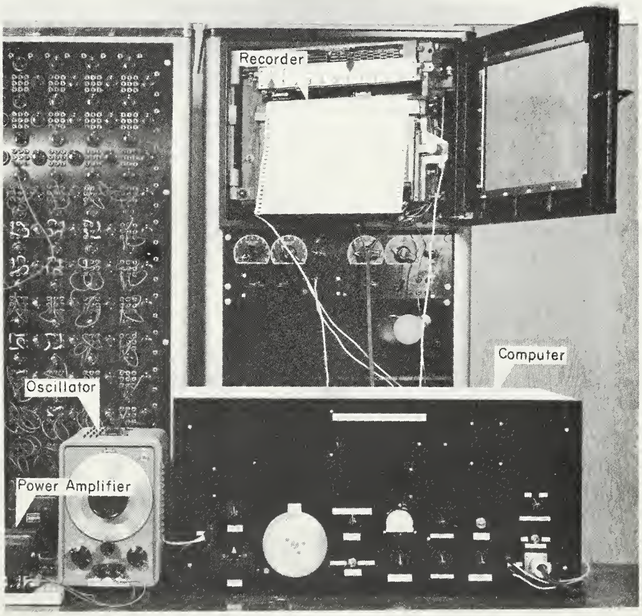


FRONT



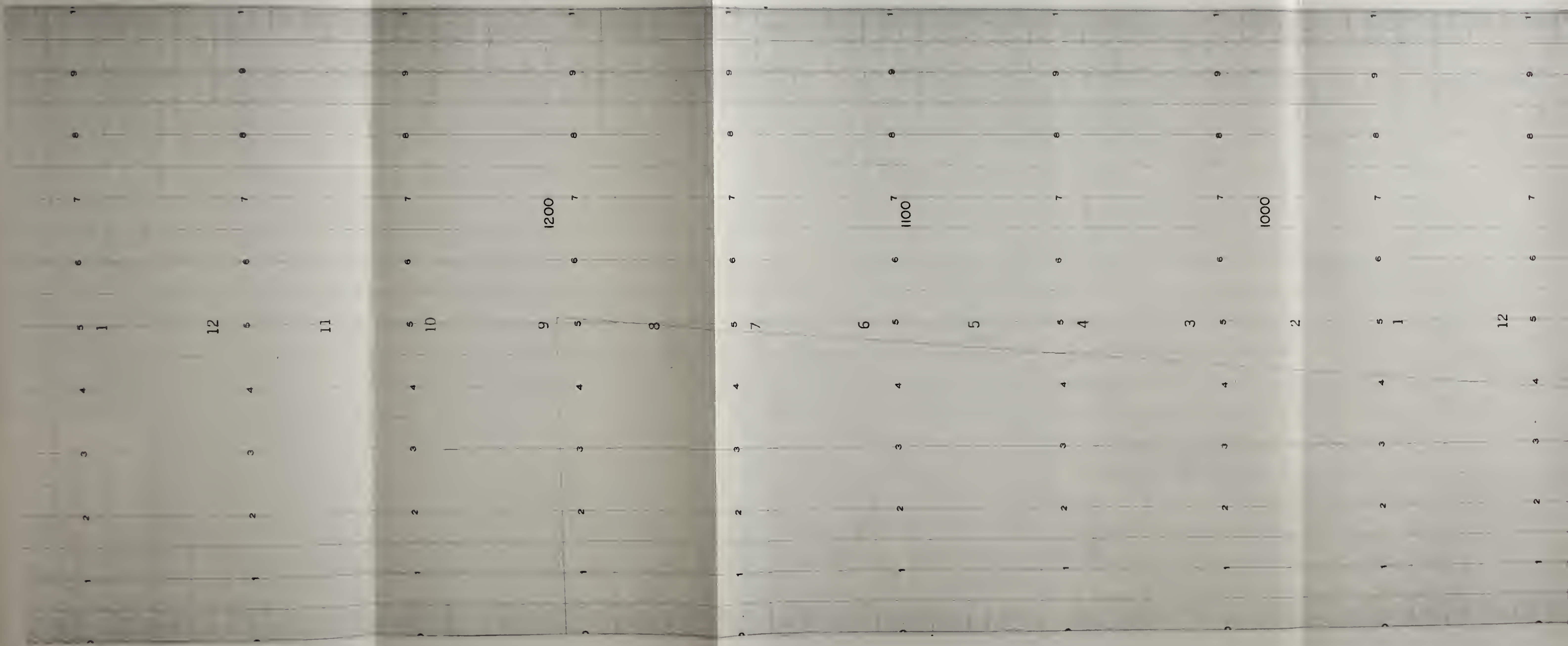
REAR

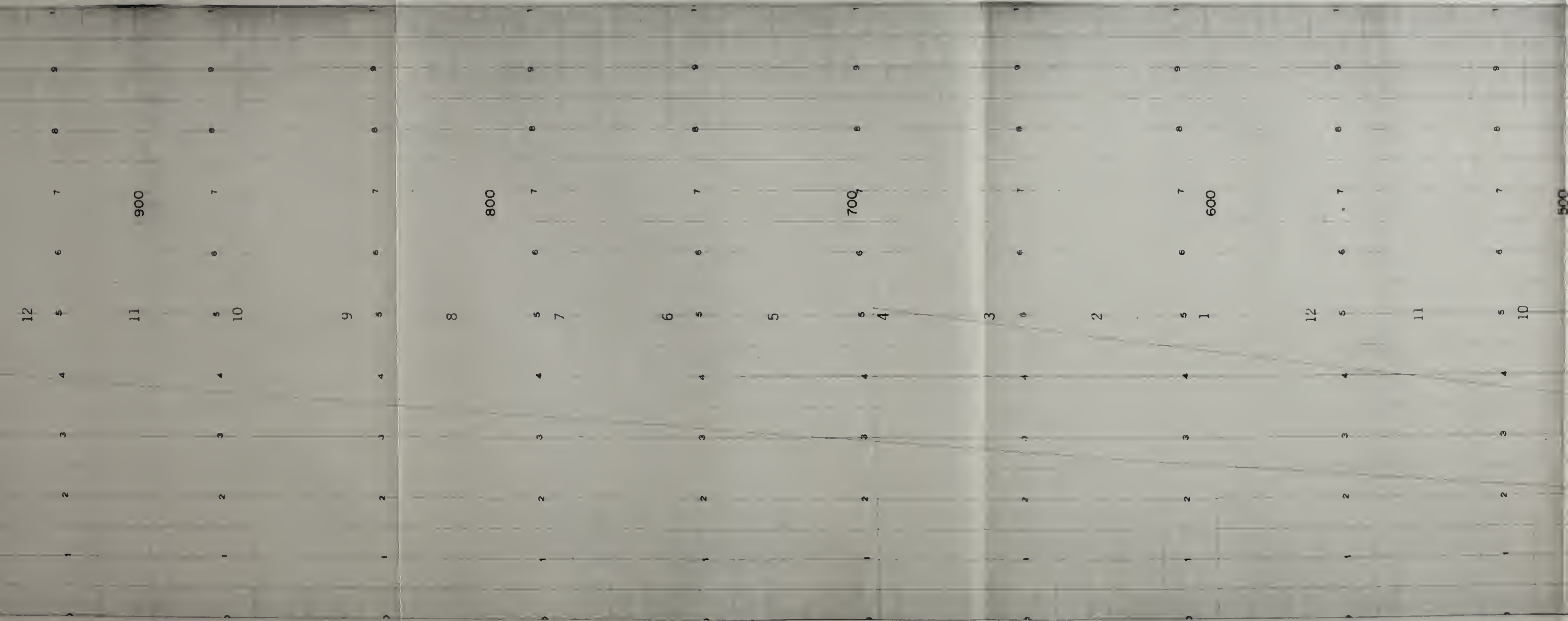
RECORDER



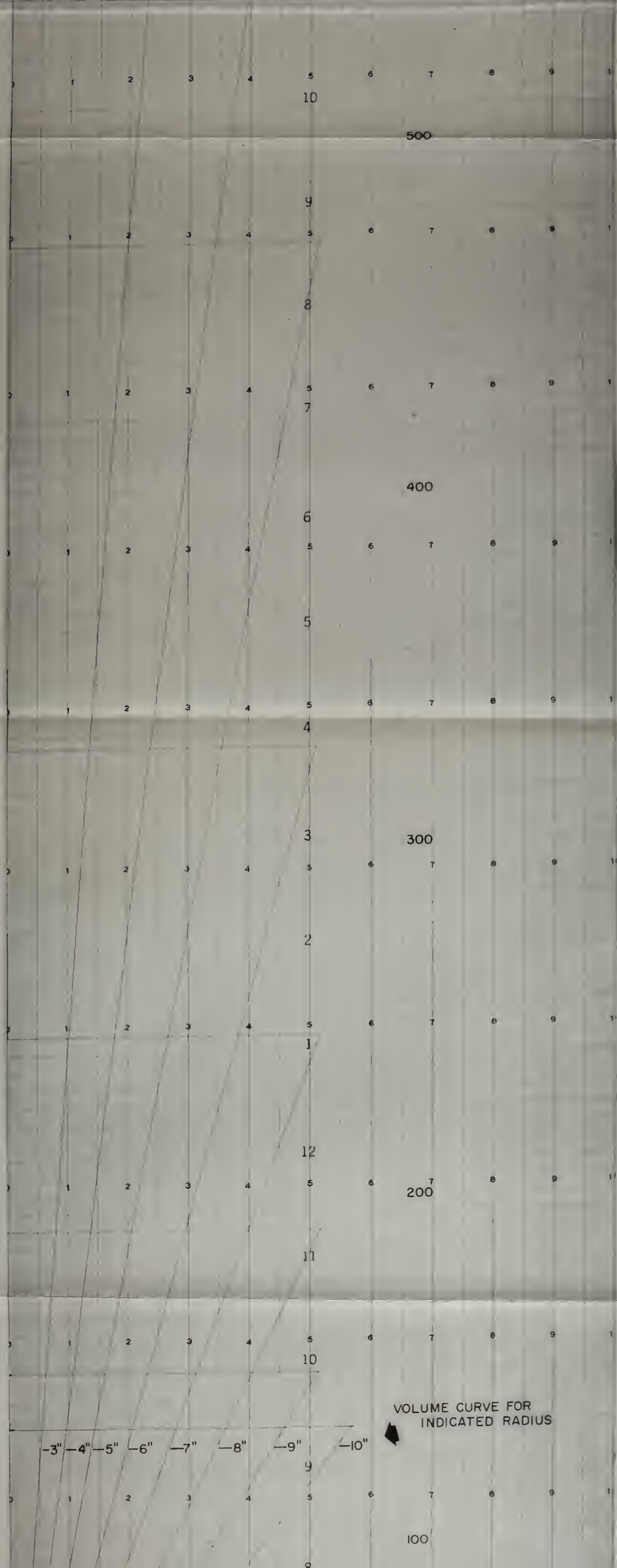
DRILL HOLE LOG SIMULATION SYSTEM

Figure 13

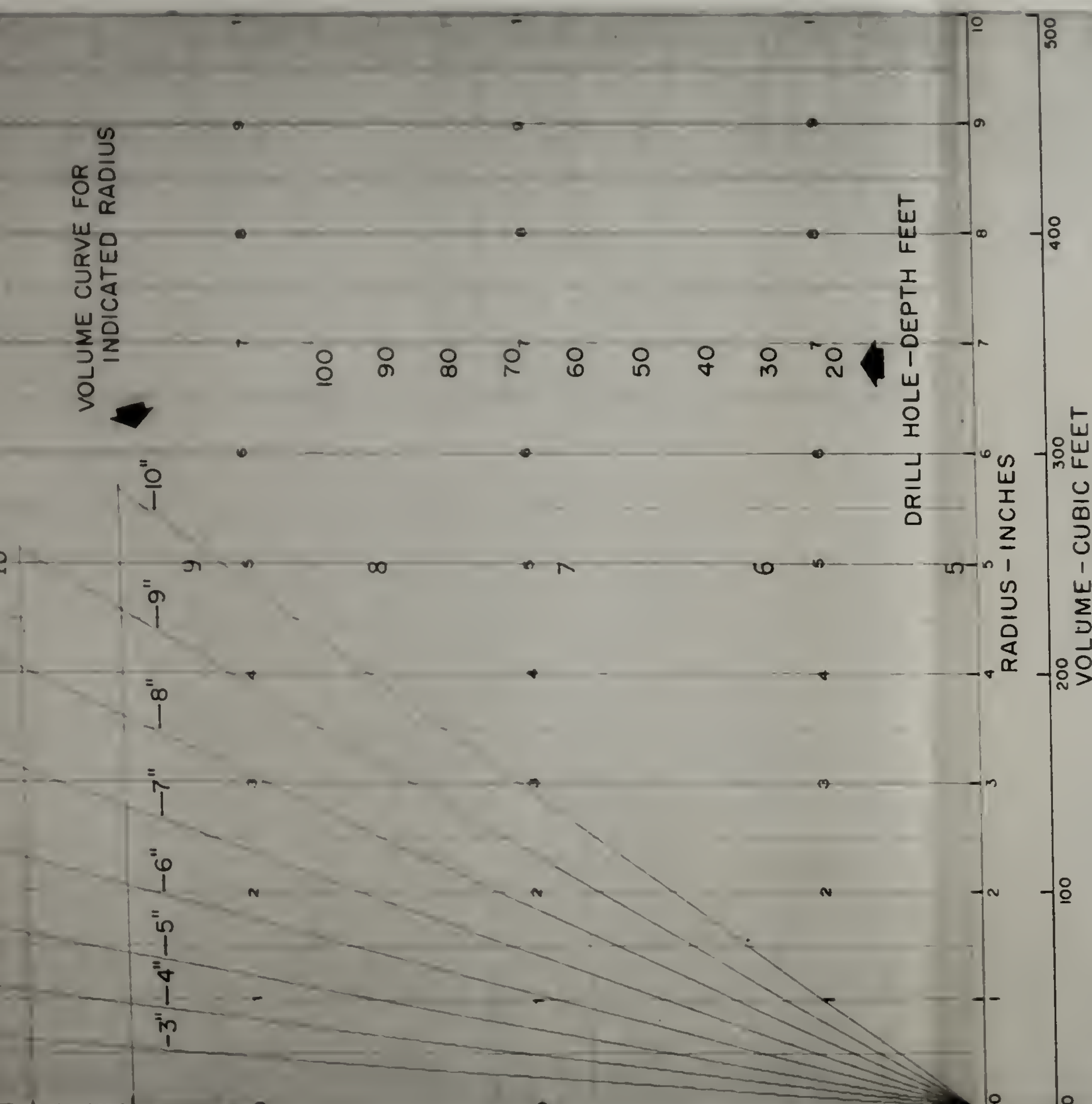

1200
1100
1000



900
800
700
600
500



500
400
300
200
100
VOLUME CURVE FOR
INDICATED RADIUS
-3" -4" -5" -6" -7" -8" -9" -10"



RECORD FROM
CONSTANT RADIUS DRILL HOLE
COMPUTER TEST

Logging Velocity = 120 ft./min.

r_{max} = 15 inches

FIG. 14

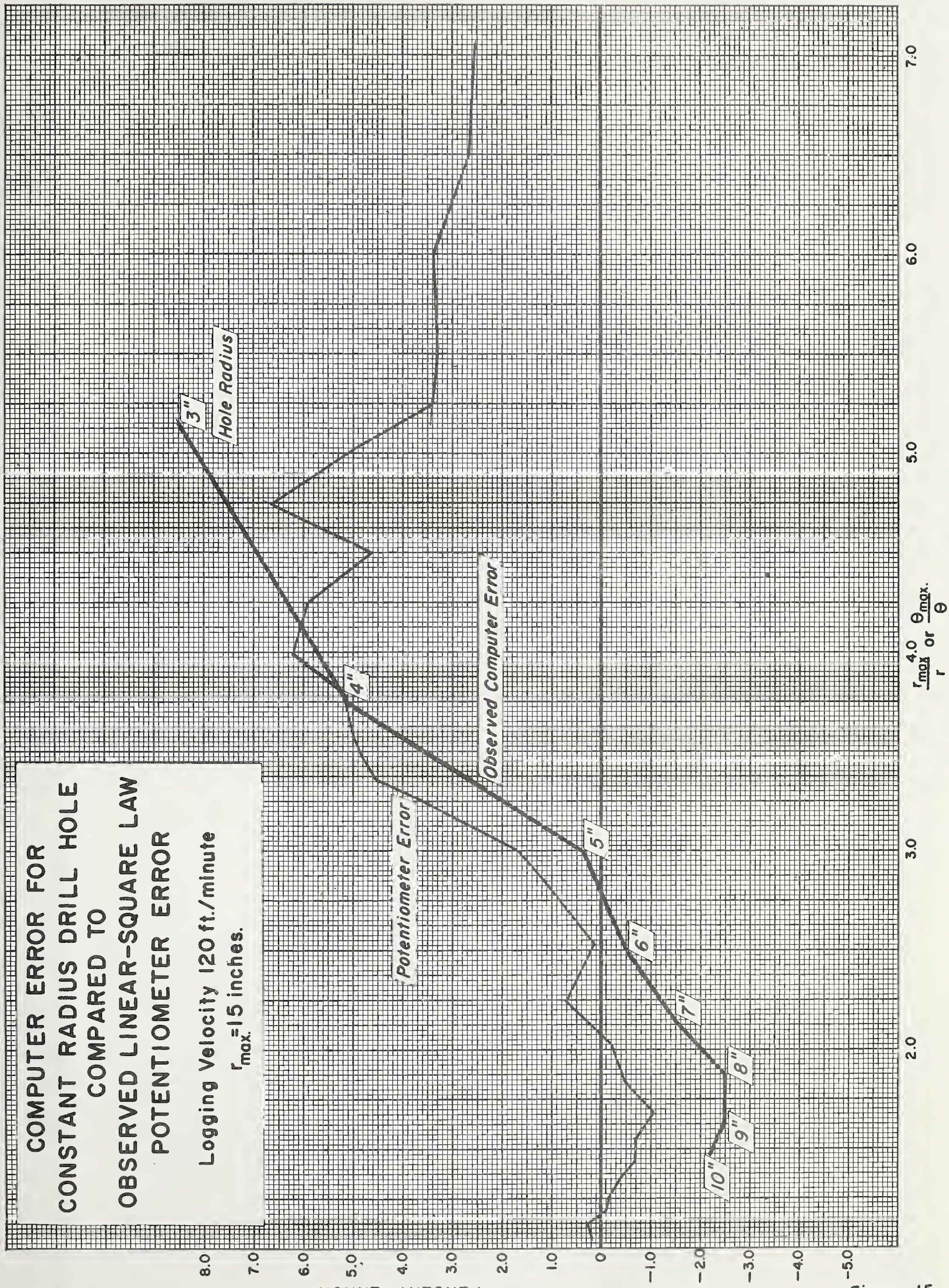
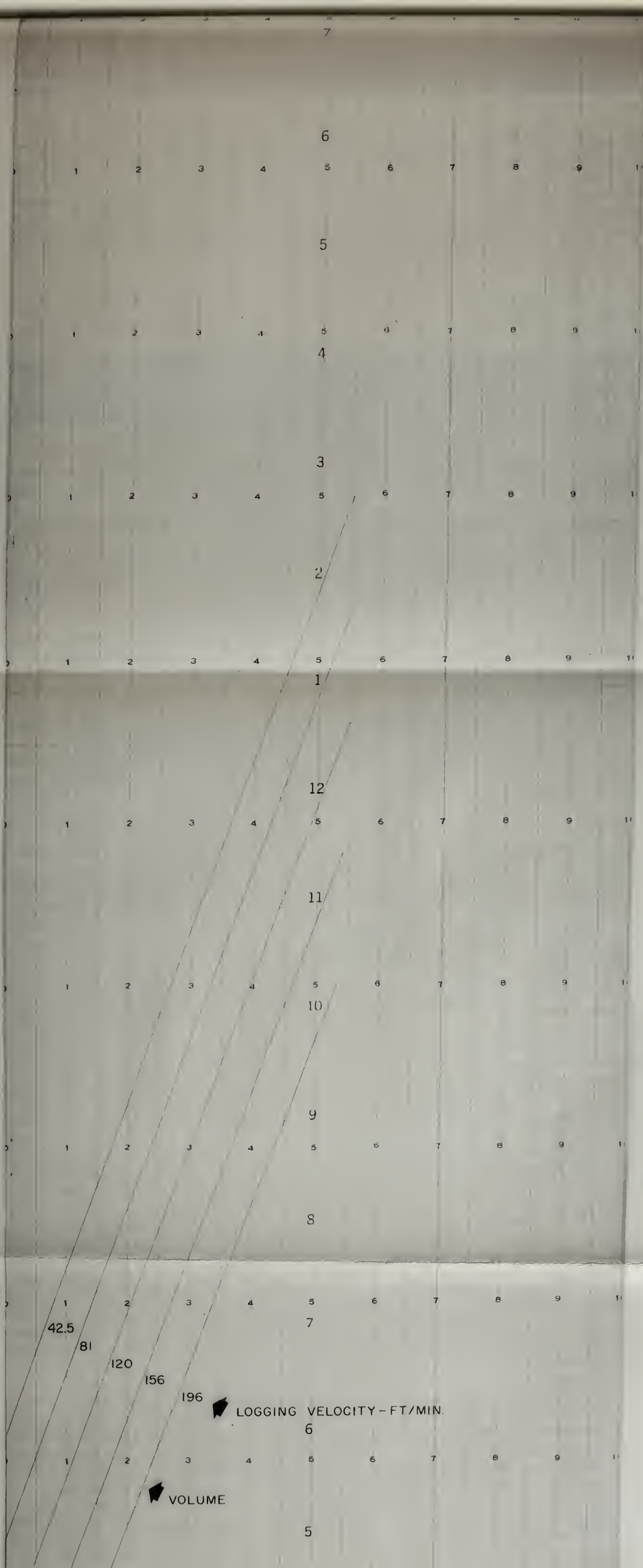
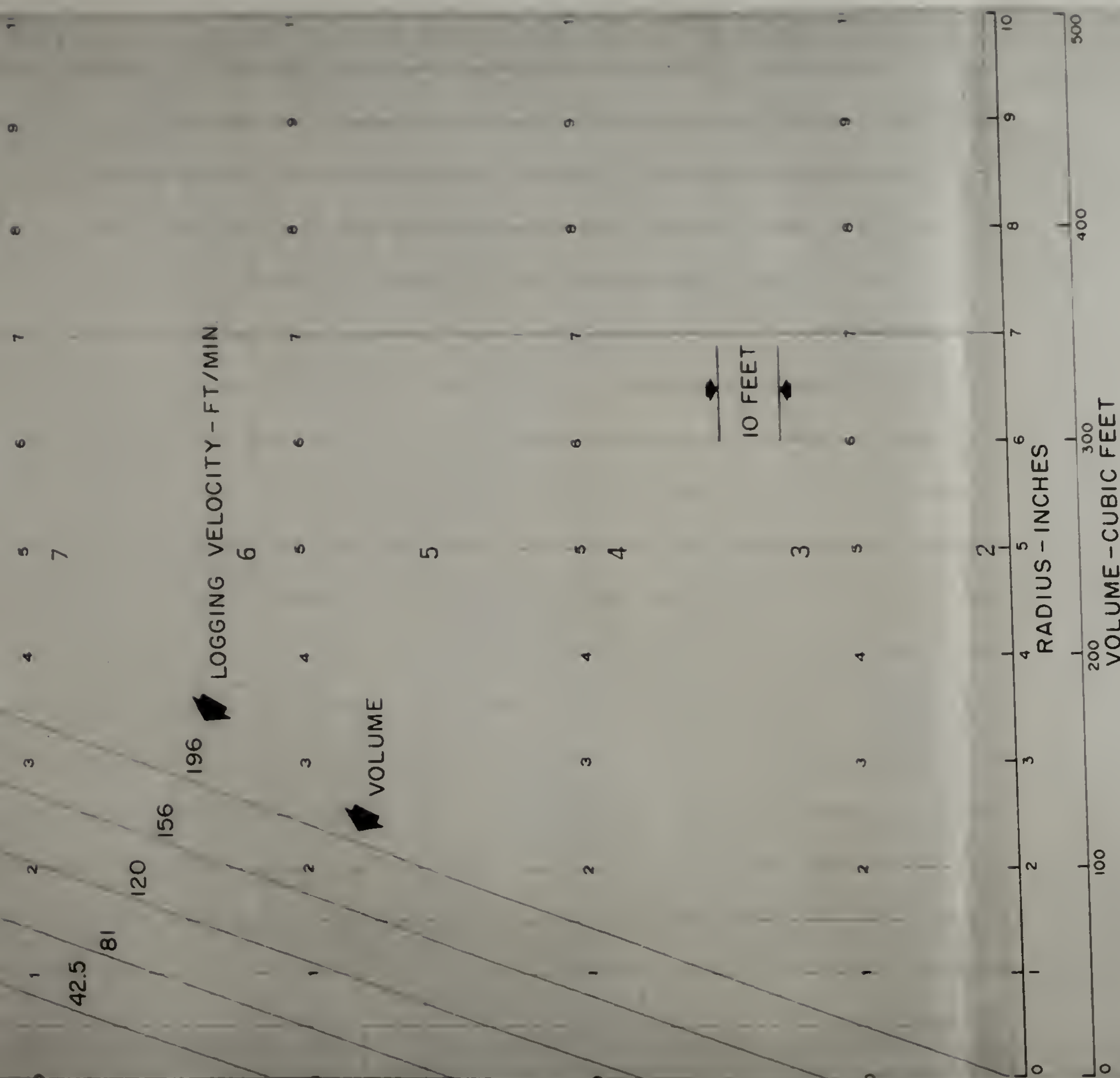

COMPUTER ERROR FOR
CONSTANT RADIUS DRILL HOLE
COMPARED TO
OBSERVED LINEAR-SQUARE LAW
POTENTIOMETER ERROR
Logging Velocity 120 ft./minute
$r_{max.}$=15 inches.
Hole Radius
3"
4"
5"
6"
7"
8"
9"
10"
Observed Computer Error
Potentiometer Error
PERCENT ERROR
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
−1.0
−2.0
−3.0
−4.0
−5.0
$\frac{r_{max}}{r}$ or $\frac{\theta_{max.}}{\theta}$
2.0
3.0
4.0
5.0
6.0
7.0

Figure 15



42.5
81
120
156
196
LOGGING VELOCITY - FT/MIN.
VOLUME



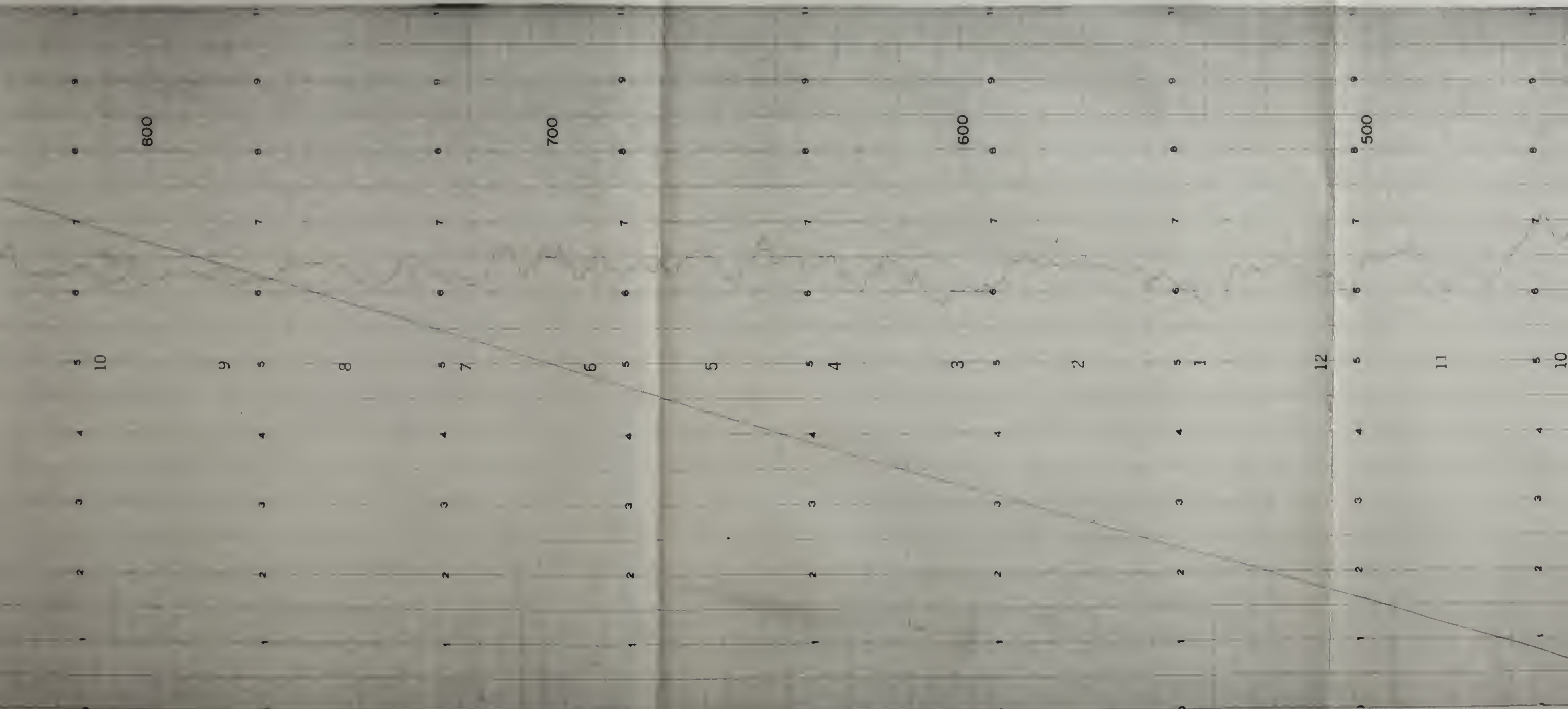
RECORD FROM VARIABLE LOGGING VELOCITY COMPUTER TEST

Drill Hole Radius = 7 inches

$r_{max.}$=15 inches

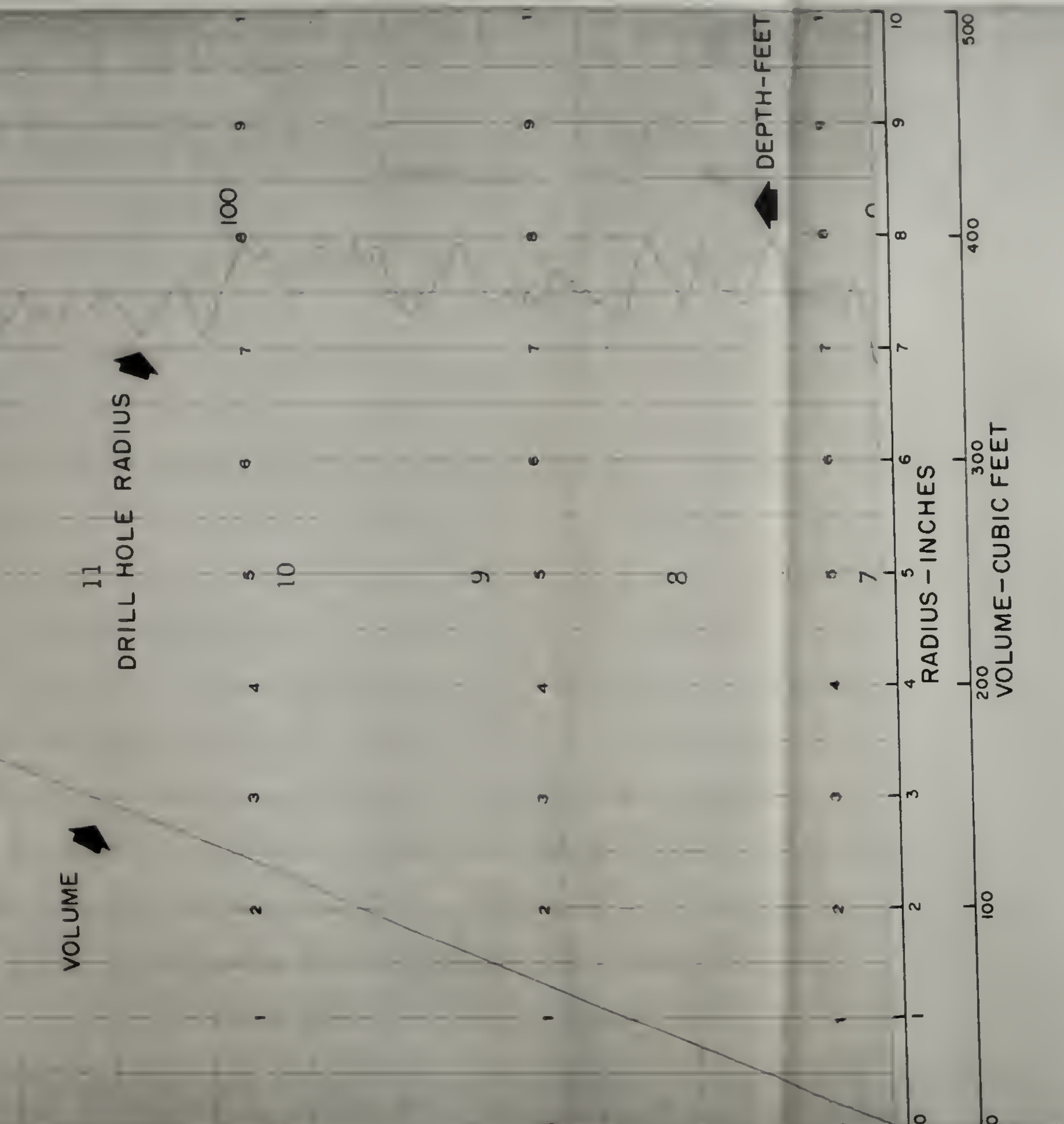
FIG. 16


1000
900
800



800
700
600
500

500
400
300
200
100
VOLUME
DRILL HOLE RADIUS



RECORD FROM SIMULATED LOGGING RUN

Logging Velocity = 120 ft./min.

$r_{max.} = 15$ inches

FIG. 17

NOMENCLATURE

a	A constant
b	A constant
C	Capacitance, farads
e	Voltage, volts
E	Voltage, volts
E_C	Integrating capacitor voltage, volts
E_{slp}	Voltage output from square law potentiometer, volts
E_T	Voltage output from tachometer
i	Current, amperes
P	The operator $\frac{d}{dt}$
q	Charge, coulombs
r	Drill hole radius, feet
R	Resistance, ohms
R_L	Leakage resistance of integrating capacitor, ohms
t	Time, seconds
t_i	Maximum period of time over which integration proceeds, seconds
T	A specific time or a fractional tolerance
V	Volume, cubic feet
x	Distance along drill hole axis, feet
X	A specific distance
Y	A reference voltage, volts
α	A scale factor
β	A transfer function
ε	An error, fraction
θ	Angular shaft displacement, degrees
ω	Angular velocity, degrees/second

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APPENDIX A

The Halliburton Oil Well Cementing Company Caliper Logging Tool Output Signal

The Halliburton caliper logging tool presents an output signal of the form:

$$E_o = ar + b \qquad \text{.......(A-1}$$

where E_o = caliper tool output voltage

r = drill hole radius

a, b = constants

The magnitude of the output signal for a given radius is not fixed and may be varied at the option of the logging operator, but its range is between zero and one volt as the drill hole radius varies from its minimum to its maximum diameter. The output impedance of the circuit from which E_o is derived is of the order of 100,000 ohms.

The constant a in Equation A-1 is under the control of the operator but the constant b is fixed by the construction of the individual logging tool. Since the logging tools must be interchangeable among various logging trucks, Halliburton have devised a system whereby the logging tool which is to be used with a particular truck is calibrated before each run.

The calibration is effected as follows.

i. When the arms of the logging tool are fully closed, the effective radius at the extremities of the arms in 1.5 inches. A zero off-set control on the recording equipment is then adjusted

so that the radius recorded is 1.5 inches. This adjustment accounts for the constant b in Equation A-1 and the input to the recorder is now a signal proportional to the drill hole radius or:

$$E_r = E_o - b = ar \qquad \text{.........(A-2}$$

ii. A ring of known radius is now placed over the caliper tool and the arms of the tool are extended until they are constrained by the ring. The sensitivity of the recording equipment is now adjusted until the recorder indicates the known radius of the ring. This adjustment accounts for the constant a in Equations A-1 and A-2 and the recording equipment is now calibrated for use with the given caliper tool.

APPENDIX B

Detailed Discussion of the
Drill Hole Volume Computer Circuit

A. DISCUSSION OF CIRCUIT

The circuit of the drill hole volume computer as finally evolved is shown in Figure B-1. The circuit may be divided into three general sections: the computer proper, the vacuum tube voltmeter and the integrating capacitor discharging trigger circuit. These sections will be discussed separately.

i. The Computing Section

With the exception of the input circuit, the computing section is similar to the basic circuit of the computer as shown in Figure 5.

Servo amplifier 1 is preceded by a preamplifier which matches the relatively high impedance caliper tool to the low impedance input of the servo amplifier. The preamplifier tube V_1 is connected as a cathode follower and has an output impedance of approximately 500 ohms. The impedance seen by the amplifier is the output impedance of the cathode follower plus the capacitive reactance of the coupling capacitor C_2 or a total of about 3000 ohms. The grid of V_1 is connected to the reed of the converter which is driven by the converter coil so as to vibrate between contacts 3 and 5 at a rate of 60 times per second. When the reed is on contact 3, the grid capacitor C_1 charges to the voltage which appears on contact 3 at that instant. When the reed is on contact 5, the grid capacitor is discharged. Thus a voltage appearing on contact 3 is chopped into a 60 cycle per second voltage which is passed on to the input of the servo amplifier. The amplified voltage is fed to the servo motor 1. The amplifier and servo motor comprise a conventional servo system (17) with the motor turning in one direction if contact 3 is

positive with respect to ground and in the reverse direction if the polarity of contact 3 is negative. If the voltage on contact 3 is zero, the motor is not excited.

The potential of contact 3 is equal to the caliper tool output voltage minus the voltages appearing across the off-set resistor R_7 and the precision linear potentiometer R_1. The latter voltage is controlled by the rotation of the shaft of R_1 which is driven by servo motor 1. The off-set resistor voltage compensates for the fact that the output from the Halliburton caliper tool is not zero when the drill hole radius is zero, as discussed in Appendix A. It is adjusted in a manner to be described later. The action of the servo system balances the voltage drop across R_1 against the caliper tool voltage minus the off-set voltage, the difference between the latter being proportional to the drill hole radius. Thus the shaft rotation of the linear potentiometer is made proportional to the drill hole radius. The constant of proportionality is determined by the span resistor R_9 and its adjustment to obtain a constant of proportionality equal to the previously fixed scale factor α_1 is described later.

The remainder of the computer circuit is identical to Figure 5 and its operation has been discussed in Section III C, Subsections ii and iii.

The computer tachometer is driven by the selsyn motor whose rotor and stator windings are connected to those of the logging truck selsyn generator.

ii. <u>The Vacuum Tube Voltmeter Section</u>

The galvanometers of the Halliburton recording camera require

one milliampere for a full scale deflection. This current is provided by the vacuum tube voltmeter tube V_3. The grid of V_3 is connected between the integrating capacitor and ground when the VTVM Function Switch is in the 'Run' position.

The vacuum tube voltmeter tube V_3 is connected as a cathode follower. Its plate is connected directly to the 400 volt supply while its screen grid is maintained at a constant potential with respect to its cathode by means of a 45 volt battery. The latter connection gives the tube a constant current characteristic which ensures that the plate current is a function only of the control grid potential and is insensitive to variations of the plate to cathode voltage. The galvanometer of the Halliburton recording camera is connected in series with the cathode circuit of V_3 and the cathode resistor R_{12} is chosen such that one milliampere flows in the cathode circuit when the grid of V_3 is at its maximum potential with respect to ground. The maximum grid voltage is equal to the maximum integrating capacitor voltage which has been chosen as 300 volts. Since V_3 operates as a cathode follower, its maximum cathode to ground voltage is nearly 300 volts and thus the required cathode resistor for a one milliampere current is approximately 300,000 ohms. A 280,000 ohm fixed resistor in series with an adjustable resistance of 30,000 ohms was used as the cathode resistor in order to afford some degree of adjustment. Although the large cathode resistor of V_3 results in excellent VTVM linearity, the cathode current does not go to zero when the grid to ground voltage of V_3 is zero. Thus a zero adjusting circuit comprising a 3 volt battery, potentiometer R_{10} and resistor R_{11} is provided. This combination causes a current to flow in the galvanometer circuit which is in the opposite direction to the residual VTVM cathode current. The adjustment is made when the

Function Switch is in the 'Zero' position. A means of internal calibration of the VTVM is provided by the meter M and the Full Scale Voltage Set potentiometer R_{16}. Adjustment of R_{16} in conjunction with Meter M permits 300 volts to be applied to the VTVM tube when the Function Switch is in the 'Calibrate' position. Adjustment of the VTVM Range resistor R_8 after the VTVM has been zeroed calibrates the full scale deflection of the camera galvanometer.

It should be noted that the VTVM measures the voltage between the upper plate of the integrating capacitor and ground and not the voltage across the capacitor alone. This introduces a maximum error of 0.13 per cent of full scale in the output when a hole having the maximum radius is being logged. The convenience afforded by measuring the capacitor voltage with respect to ground outweighs this small contribution to the total error of the computer.

iii. The Capacitor Discharging Trigger Circuit

As discussed in Section IV-D, the integrating capacitor is discharged after it reaches its maximum voltage, the process being repeated as logging progresses. This is accomplished by the trigger circuit which is described below.

Tubes V_4 and V_5 comprise a direct coupled amplifier which controls the grid to cathode voltage of a thyratron V_6. When the first grid of V_4 is positive with respect to the lower end of R_{25}, the first triode of V_4 conducts heavily, and the resulting voltage drop across R_{25} causes the second triode of V_4 to be cut-off. This raises the potential of the second grid of V_5 causing the second triode of V_5 to conduct heavily. The resulting voltage drop across R_{27} biases the thyra-

tron grid very negatively with respect to its cathode and the thyratron is in a non-conducting state. If the potential of the lower end of R_{25} now rises toward the potential of the first grid of V_4, the first triode of V_4 will conduct less heavily and the second triode of V_4 will start to conduct. This will result in the second triode of V_5 approaching cut-off and thus the potential of the thyratron grid will approach that of its cathode. The thyratron will then conduct, closing the relay in its plate circuit and discharging the integrating capacitor through R_{30}.

It will be noted that the potential of the first grid of V_4 is held positive with respect to ground by the Trigger Voltage Set potentiometer R_{19}. The lower end R_{25} is connected to the cathode of the VTVM tube V_3. Since V_3 is connected as a cathode follower, its cathode potential follows the potential of the integrating capacitor. As long as the cathode potential of V_3 is lower than the voltage set on R_{19}, the thyratron will not conduct. As the potential of the integrating capacitor rises, however, the cathode potential of V_3 will follow and when it reaches the potential of the slider of R_{19}, the thyratron will fire and the integrating capacitor will be discharged. As the integrating capacitor discharges, the trigger circuit resets itself and it is ready for the next operation. The length of time the discharge relay is closed is governed by the size of capacitor C_3 which is connected across the discharge relay coil. The value shown keeps the relay closed for approximately 100 milliseconds which ensures adequate discharging of the integrating capacitor.

The triggering point is set by first switching S_1 to 'Calibrate' and adjusting R_{16} so that the meter reads 300 volts. The Trigger

Voltage Set potentiometer R_{19} is then adjusted with the Trigger Function Switch on the 'Set' position until the relay just closes as indicated by the relay pilot lamp. The relay will now operate when the capacitor voltage reaches 300 volts.

The integrating capacitor may be discharged manually by turning the Trigger Function Switch to the 'Discharge Capacitor' position.

iv. Power Requirements

The computer requires two D.C. voltage supplies. The pre-amplifier tube, current controller tube, VTVM tube and two voltage dividers are supplied from a conventional 400 volt vacuum tube regulated power supply. The trigger circuit requires 400 volts which is isolated from ground but the latter voltage does not require regulation. The thyratron plate circuit is powered by 117 volts A.C. obtained from an isolation transformer, while its heater circuit is supplied from a separate source of 6.3 volts A.C. The Minneapolis-Honeywell servo amplifiers have self contained power supplies and require only 117 volts A.C. The total A.C. power consumption of the computer is estimated as 120 watts.

In addition to the A.C. power requirements noted above, the computer requires 3 - 3 volt batteries, 2 - 45 volt battereries and one 90 volt battery. Although not shown on Figure B-1, provision is made for disconnecting the batteries from their resistive loads by means of a multipole switch.

Table B-1 is a list of the components used in the construction of the computer. A photograph of the interior of the computer is shown in Figure B-2.

B. THE COMPUTER PANEL CONTROLS

A photograph of the computer operating panel is shown in Figure B-3. The following is a description of the computer operating controls and an outline of their functions.

Off-set Adjust	Compensates for the caliper tool output voltage not going to zero for a drill hole with zero radius. Off-set voltage variable from zero to 300 millivolts.
Span Adjust	Adjusts angular rotation span of linearpotentiometer so that design radius scale factor is obtained. Accepts caliper tool signal magnitude range of 300 millivolts = 15 inches to 3 volts = 15 inches.
Radius Indication Dial	Indicates drill hole radius in inches. Used to assist in the calibration of the computer.

VTVM Function Switch

a) Zero position: Shorts VTVM input for zeroing.
b) Run position: Connects VTVM to integrating capacitor.
c) Calibrate position: Connects VTVM to source of 300 volts for VTVM calibration purposes.

VTVM Zero Adjust	Zeros VTVM circuit.
VTVM Span Adjust	Adjusts full scale range of VTVM.
Full Scale Voltage Set	In conjunction with meter, provides a source of 300 volts for VTVM range and trigger voltage setting purposes.
Trigger Voltage Set	Controls voltage at which integrating capacitor discharge relay closes.

Trigger Function Switch

a) Run-Set position: Makes trigger circuit operative for running caliper log or for setting trigger voltage.

b) Discharge Capacitor position: Permits integrating capacitor to be discharged manually.

C. OPERATING INSTRUCTIONS

The following is a description of the operations which must be performed in order to calibrate and use the computer for logging a drill hole. It is assumed that the computer is connected to the appropriate caliper logging equipment.

1) The computer power supplies are turned on and the computer is permitted to warm up for a few minutes.

2) The Off-set Adjust control is set to the approximate off-set voltage characteristic of the particular caliper tool in use. If the off-set voltage is not known, the control is set at mid-scale.

3) With the calibrating ring over the arms of the caliper tool, the Span Adjust control is varied until the radius of the calibrating ring is indicated on the Radius Indicator Dial.

4) With the arms of the caliper tool closed, the Off-set Adjust control is varied until the Radius Indicator Dial indicates 1.5 inches.

5) Steps 3 and 4 are repeated until no further adjustment of the Off-set or Span Adjust controls is required.

6) The VTVM Function switch is turned to the Zero position and the VTVM Zero control is adjusted to bring the camera galvanometer to its zero reference position.

7) The VTVM Function switch is turned to the Calibrate position and the Full Scale Voltage Set control is adjusted until the meter reads 300 volts.

8) The VTVM Span control is adjusted until the camera galvanometer deflects to its full scale position.

9) With the Trigger Function switch on the Run-Set position, the Trigger Voltage Set control is adjusted until the discharge relay closes as indicated by the lighting of the discharge relay pilot lamp.

10) The Trigger Function Switch is turned to the Discharge Capacitor position.

11) The VTVM Function Switch is turned to the Run position.

12) Just before commencing a logging run, the Trigger Function switch is turned to the Run position.

The drill hole volume computer is now ready for logging to start.

13) Upon completion of logging, the Trigger Function Switch may be turned to the Discharge position and the computer power supplies de-energized.

TABLE B-1

List of Parts used in the
Drill Hole Volume Computer

V_1	12AU7
V_2, V_3	6AU6
V_4, V_5	12AX7
V_6	2D21
R_1	10 K Precision linear potentiometer, tolerance 0.5% Technology Instrument Corporation RV 1 5/8
R_2	10 K Precision square law potentiometer, conformance 0.5% Technology Instrument Corporation RV 1 5/8 - S347
R_3	2530 ohm 0.1% Low temperature coefficient
R_4	10 K Potentiometer with 25% tap. Technology Inst. Corp. RV-2
R_5	1 K ½w 5%
R_6	2 K 2w 10%
R_7	1 K Potentiometer, wire wound
R_8	10 K Potentiometer, wire wound
R_9	100 K Potentiometer, wire wound
R_{10}	25 K Potentiometer, wire wound
R_{11}	100 K ½w 5%
R_{12}	280 K ½w 1% Deposited carbon
R_{13}	30 K Potentiometer, wire wound
R_{14}	6 M ½w 1% Deposited carbon
R_{15}, R_{18}	7.5 K 10w wire wound, adjustable
R_{16}, R_{19}	5 K Potentiometer, wire wound
R_{17}, R_{20}	30 K 10w wire wound
$R_{21\ 22\ 23\ 27\ 29}$	1 M ½w 5%
R_{24}	2 M ½w 5%
R_{25}	27 K ½w 5%

R_{26}	47 K $\frac{1}{2}$w 5%
R_{28}	470 K $\frac{1}{2}$w 5%
R_{30}	10 ohms 10w wire wound
R_k	400 K $\frac{1}{2}$w 1% Deposited carbon
R_s	100 K 0.25% Low temperature coefficient
C	20 mfd (Nominal) 400 WV Stabelex D Industrial Condenser Corporation
C_1	.001 mfd Ceramic
C_2	1 mfd paper
C_3	40 mfd 600 WV Electrolytic
S_1	1 pole, 3 position switch, ceramic insulated
S_2	1 pole, 2 position switch
T	Isolation transformer, 117V-117V, 100 milliamperes
Servo Amplifiers (2)	Minneapolis-Honeywell Brown No. 356358-1
Servo Motors (2)	Minneapolis-Honeywell Brown No. 76750-3
Converter	Minneapolis-Honeywell Brown No. 75829-1
Selsyn Motor	General Electric Model 2JD123A10A
Tachometer	Instrument Motors Inc. Model M-24-012
M	0 - 50 microampere meter

Notes:

K = 1000 ohms

M = 1,000,000 ohms

w = watt

WV = working voltage

CIRCUIT DIAGRAM
OF
DRILL HOLE VOLUME COMPUTER

NOTES : $K = \times 10^3$
$M = \times 10^6$

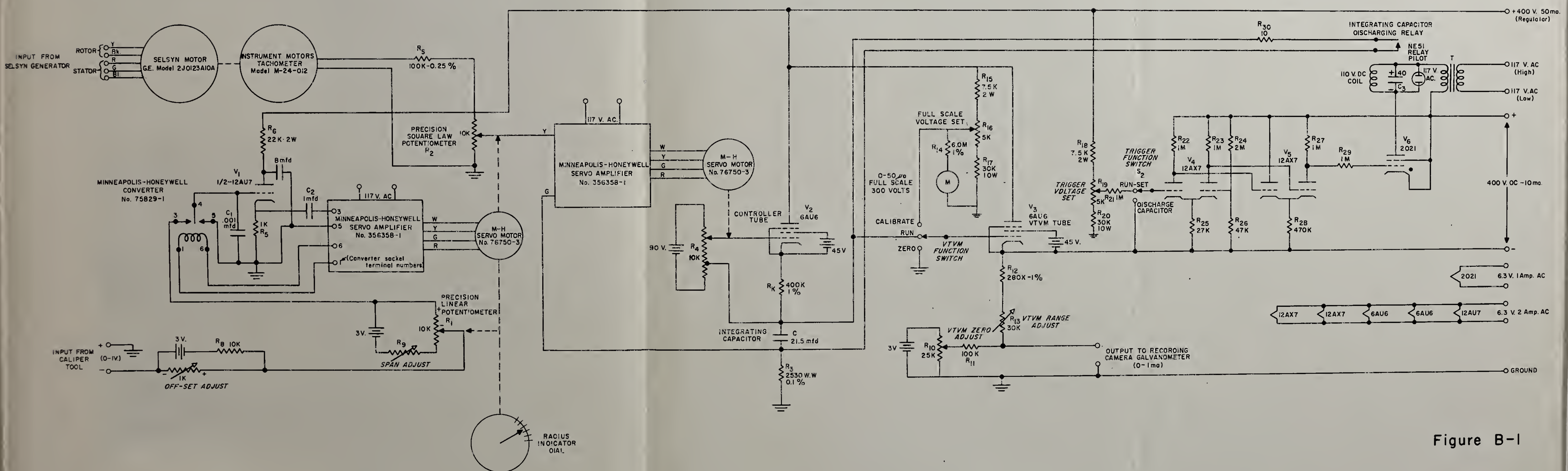
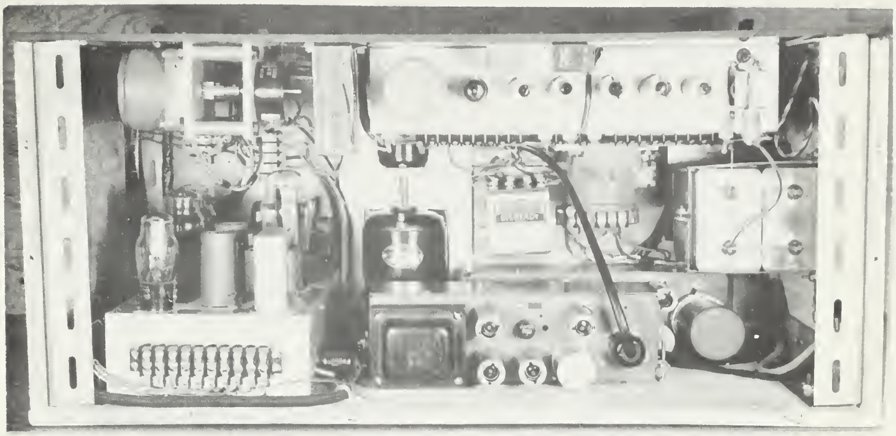
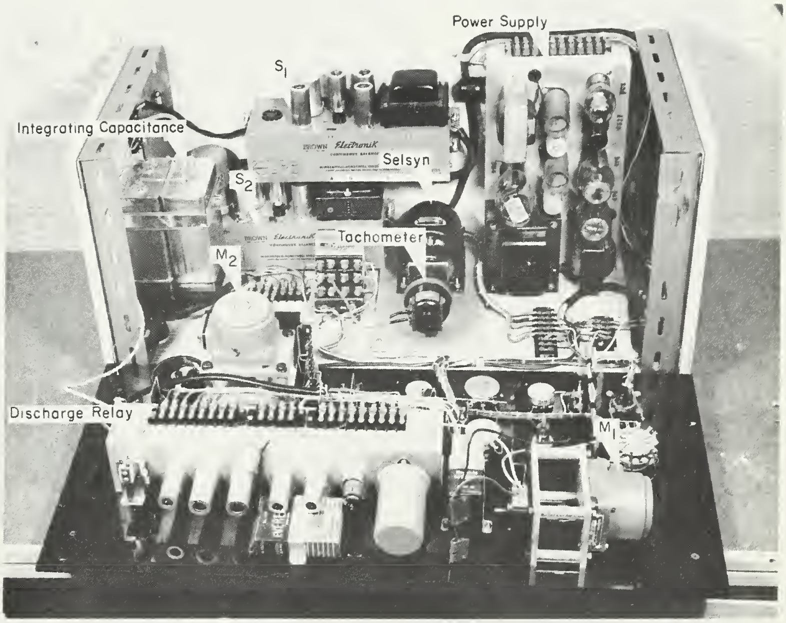


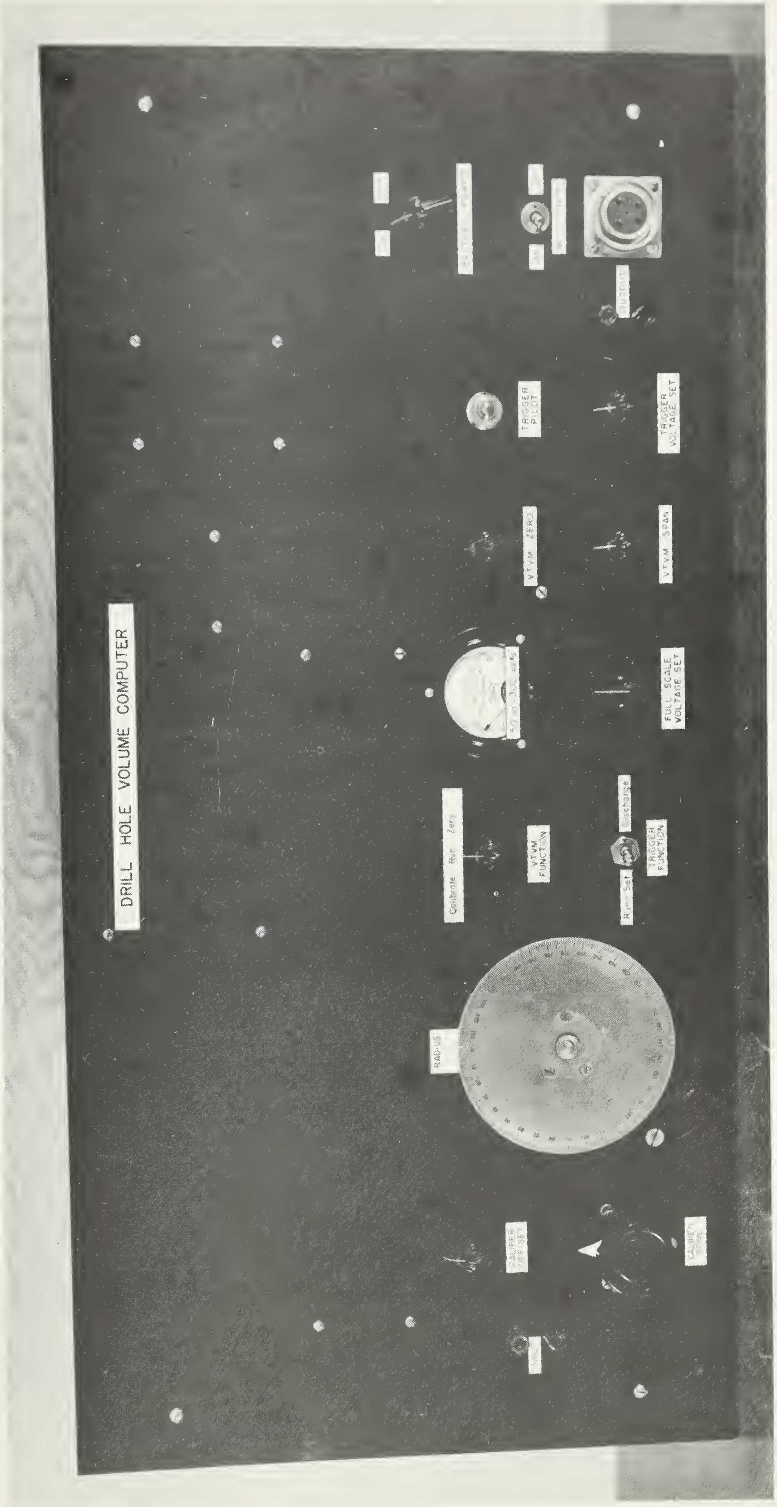
Figure B-1





INTERIOR OF DRILL HOLE VOLUME COMPUTER

Figure B-2



COMPUTER OPERATING PANEL

Figure B-3